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DEVELOPMENT OF A DESIGN ENABLER TOOL FOR FRAME ANALYSIS FOR A SMALL ENTERPRISE: A CASE STUDY

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Mechanical Engineering

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by
Madhusudan Ranjan Kayyar
December 2007

Accepted by:
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Dr. Lonny L Thompson

ABSTRACT

This case study investigates the design process followed by a small to medium scale enterprise (SME) that primarily depends on special expertise in the form of a few key individuals. These individuals design products mainly based on past experience, augmented by trial and error. This is an inefficient, time consuming, and expensive way of designing products and evaluating their performance. This study critiques the different steps in the current design process, identifying areas of potential improvement and enhancement through application of formal design methods and innovative design enablers. The "Design Enablers" are design tools that assist the designer at various phases of the design cycle. The design enabler could be as simple as a requirements checklist or as complex as a customized computer based analysis tool. The findings from the case study led to the development of a specialized design enabler that facilitates computer aided engineering analysis of frames, noticeably absent in the SME's current design process. The tool would empower the frame designer to analyze different frame configurations under various simulated operating conditions. The designer is then able to rank different designs based on the stress, deflection, cost, number of members and joints, and other quantitative and qualitative factors. This tool can be termed as a virtual prototyping tool. The designer is able to determine the merits and demerits of a frame design without actually having to physically build it and subject it to a test. With the aid of the design enabler, the frame designer is able to arrive at a goodness measure for a frame based on engineering analysis rather than basing the design purely on his experience. The goodness measure can be defined as the percent deflection lower than the

deflection limit value. The deflection limit value can be determined from an analysis of a frame configuration that is currently being used in the field without failures. The extensive use of the design enabler tool would result in the management making an informed decision on costing, finalizing the frame design and WMP would have greater confidence while testing and designing the frames. Furthermore, the design enabler forms the foundation for extending the scope to include rule-based systems, optimization and case based reasoning that would assist designers in efficient product development

DEDICATION

This research work is dedicated to my wife Deepa for her unconditional love, encouragement and support, our son Maitreya whose love towards us seems like an endless ocean, my parents who have raised me to be the person I am today, to my brother and loving memory of my grandparents.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to Dr. Joshua Summers and Dr.Sherrill Biggers for their guidance, encouragement and support throughout my graduate studies. I would like to thank Dr.Lonny Thompson for being a part of the committee. I would like to thank all my committee members for their patience in reviewing my thesis and providing valuable suggestions for improving it. I am also grateful for the support of the industrial collaborators for this research, namely Wright Metal Products. A special thanks to my fellow graduate student Min Wang for extending his selfless help for developing the graphics module for this work. I would also like to thank my friends Shyam Panyam, Nitendra Nath, Uday, and Suneela for their help during my illness. Finally, I would like to thank my family, friends, and colleagues for their constant support throughout my graduate schooling.

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CHAPTER 1

INTRODUCTION

Product development in any organization relies on well-established scientific and engineering knowledge; the true hallmark of any successful big businesses found in the form of well-established databases and experienced personnel. The design database is developed over the years capturing the knowledge of experienced individuals and groups over time. The design knowledge database comprising design practices, best practices, product databases, procedural templates, patents, design rules, and test data that form the core of the design process. However, in many small and medium scale enterprises (SMEs), engineering knowledge is primarily special expertise in a specific product area in the form of an experienced employee, who may not even be an engineer. In such cases, design decisions and product innovations are primarily developed from experience-based reasoning with little or no engineering tools applied.

In the US alone, a total of 225,139 SMEs exported goods in 2004, accounting for 97 percent of all U.S. exporters and 28.6 percent of goods exports in 2004[1]. Furthermore, at the start of 2004, SMEs accounted for more than half (51.3%) of the UK's estimated business turnover of £2,400billion (small enterprises accounting for 37%; medium-sized enterprises accounting for 14.3%)[2]. Most of the SMEs primarily depend on their experienced work force for product development while typically not investing heavily on specialized personnel with expertise on computer aided design tools. It becomes imperative to develop some specialized and affordable design tools–Design Enablers.

[1] According to US Small Business Administration (http://www.sba.gov)
[2] According to UK Small Business Service (http://www.sbs.gov.uk)

Design enablers are computer aided tools could assist the SMEs experienced work force to design better products with emphasis on sound engineering principles and tools without actually having to invest in high-end commercial CAD/CAE software and personnel. Design enablers can be developed for various stages of the design process and are typically customized based on the design process specific to an organization.

This thesis serves as a case study and a critique of the design process followed by a specific SME, exploring how they develop and build custom solutions. Based on this, a new design enabler is developed to support engineering analysis which is a key aspect of the design process. This tool is specifically designed to support the current workforce with minimal amount of engineering judgment and expertise required.

This thesis tries to answer the following research questions:

- What is the design process at a typical SME which heavily depends on experience alone to design products..
- What are the key missing aspects in their current design process.
- Can a "design enabler tool" be developed for such situations where in a Company heavily relies on a few key individuals with no formal design or engineering background.

The detailed case study investigates the design process followed by Wright Metal Products (Hereafter, this SME will be referred to as WMP), in designing and manufacturing steel frames used to package and transport medium size vehicles. This process is described in Chapter 2. The design process followed at WMP, a small to medium scale enterprise (SME), primarily depends on special expertise in the form of a few key individuals who are not engineers and design products mainly based on past experience, augmented by trial and error. Chapter 2 discusses each step followed by a frame designer at WMP in designing a frame from scratch to final product realization. The typical time frame for conceptual design and prototyping a frame ranges from one to two weeks. The only design tool used in the entire design process is a CAD package for documenting the final design.

Chapter 3 answers the second research question and discusses a systematic approach to design, emphasizing a deliberate step-by-step procedure, that ensures that nothing essential has been overlooked or ignored during the design process. Chapter 3 also discusses the design process followed by Pahl and Beitz, Dixon and Poli and Ulrich and Eppinger in their design textbooks. It is observed that, the design process followed by WMP can be mapped on to the design process illustrated in Pahl and Beitz. However, the underlying tasks associated with each phase of the design process are highly person dependent in case of WMP. The use of formal design tools is almost nonexistent and suitable recommendations and potential areas of improvement through application of formal design tools have been made in Chapter 3 of this thesis. The recommendations cover four broad stages of design: customer inputs, conceptual design, prototyping, and detail design. A failure mode and effects analysis chart is presented in Chapter 3 to illustrate how certain attributes from current practices that may lead to failure in design.

One of the primary recommendations from the case study discussed in Chapters 2 and 3 is to address the lack of engineering analysis while designing the frames. The engineering analysis would enable the designer and WMP to gauge a design based on stress and deflection that the frame experiences rather basing the design purely on experience and over designing. The use of a commercial CAD/FEA package to analyze the frames would be expensive and would require special expertise to operate the package itself. The design enabler tool is built to assist the frame designer, who is not an engineer, in designing frames using engineering principles. The designer need not know the technicalities that the Tool employs to perform frame analysis. The Tool's intention is not automate the frame design process but to equip the designer with some powerful engineering tools to compute stresses and deflection in the frame before starting to prototype the concept frame. The tool is custom built for WMP and the designer needs to only input few parameters to define a frame configuration and loading conditions to obtain the stress and deformation results for the frame. Though custom built, the tool like all computer aided tools would give incorrect results if incorrect inputs are provided. The designer still needs to understand the results before proceeding with the design. To minimize such risks, a training manual has been developed and a few individuals have been trained at WMP to use the tool. The final decision making ability still lies with the designer, the tool only provides the designer with additional technical information before hand while designing a frame. Using this information the designer is able gauge the performance of the frame without actually having to prototype and subject the prototype to physical testing. Furthermore, the tool should not be viewed as a replacement to physical prototyping and testing. The results obtained from the tool can be used to bolster the test results.

The use of the Tool will save valuable time in terms of prototyping, testing and most importantly quantitatively compare different design options. This would result in significant cost and time saving for WMP. Even after implementation of the tool, the designer still takes the center stage in the design cycle. The Tool only outputs stress and deflection values and the designer still needs to interpret the results and experience would continue to play an important role in driving design decisions. The key take away for WMP from this work would be to incorporate specific design tools available in design textbooks to assist the designer at various stages of design, follow a systematic approach to designing products with special emphasis on maintaining design databases, lessons learned and documentation. The success of the design enabler tool solely lies in the hands of the designers who use it. Routine use of the Tool while designing new frames will allow the users to make valuable suggestions in improving the tool to better suit their needs and address new challenges.

CHAPTER 2

CASE STUDY

This case study investigates the design process followed by Wright Metal Products (WMP) in designing and manufacturing steel frames used to package and transport medium size vehicles. WMP (WMP) is a small to medium scale enterprise (SME) that primarily depends on special expertise in the form of a few key individuals who design products mainly based on past experience, augmented by trial and error. Designing products based on experience and trial and error was the most common method of designing adopted by most companies before systematic approaches to design were proposed by design research pioneers like Pahl and Bietz, N.Cross, Otto and Wood and Ullmann. Various models addressing a general approach to systematic design have been proposed over the past years and have been adopted by successful companies to improve design cycle time and product design. This case study will illustrate why the current design process followed by WMP is inefficient, time consuming, and an expensive way of designing products and evaluating their performance. The case study documents the current design process followed by WMP and in Chapter 3, the current design process is compared to a systematic design process. Possible changes are identified that could be adopted by WMP in improving their design process. Findings from the case study led to development of a specialized and affordable design enabler. The "Design Enablers" are design tools that assist the designer at various phases of the design cycle. The design enabler could take any form. For example, it could be as simple as a requirements checklists or a complex computer based analysis tool.

Subject of study

The SME studied is Wright Metal Products, located in upstate South Carolina. The Company designs and fabricates metal crates, or frames, shown in Figure 1 for transporting and stacking medium size vehicles. This case study investigates the existing design process followed by WMP while designing a product from start to finish. Specifically, the method adopted by the current frame designer in developing new products is described. This process is outlined in detailed flow charts based on interviews and surveys with the management, engineering, and production teams. From this, a set of limitations are identified as potential areas of opportunity that can augment the current design process with new design enablers.

WMP employs 45 people in the frame fabrication unit, has two middle level managers, and one higher-level manager. Currently the frame design is not done by engineers but by a team of two people who have worked for more than 10 years in the frame fabrication industry and are essentially frame fabricators. These designers have no formal engineering training and do not explicitly employ any engineering analysis or design tools. Their approach is comparable to artisan crafts [N.Cross].

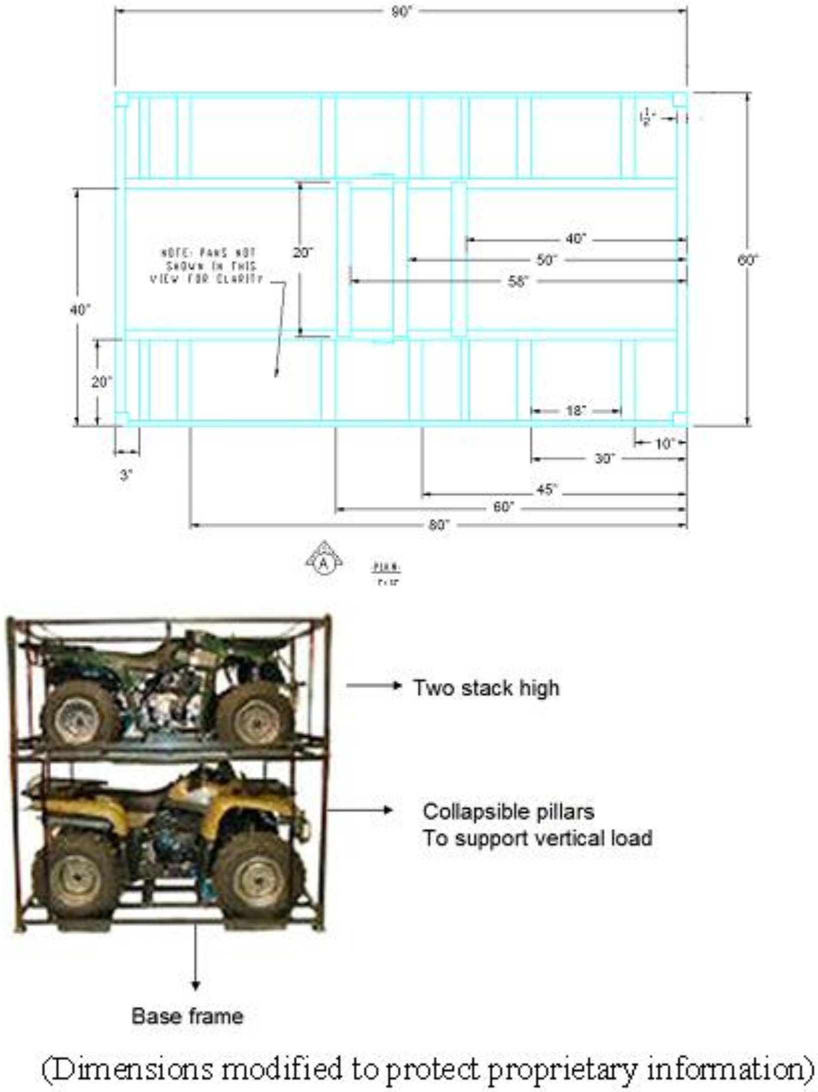


Figure 1: A typical frame designed by WMP to transport vehicles [WMP]

<u>Study method</u>

A questionnaire was prepared and used to obtain information on previous frame designs. The questionnaire covered customer requirements, basis for decisions taken while designing a frame, prototyping, and testing. The questionnaire was designed such that information was gathered from two different perspectives: the plant manager and the two shop floor frame designers. This form of triangulation is critical for case study research [Eisenhardt]. Furthermore, an interview with the frame fabricator was conducted to obtain first hand understanding of the process followed in designing a product from scratch to finish.

The following are a few sample questions:

1) Typically what inputs the customer provides at the start of the design?
2) How are preliminary specifications for the frame arrived at?
3) What are the first few steps when starting with a new design?
4) How long does it take to prototype the preliminary design?
5) What are steps in designing a frame in the absence of an earlier baseline design?
6) How does one determine the cross-sections of the frame members?
7) How does a frame designer arrive at a particular configuration?
8) What are the preliminary testing carried to verify the conceptual design?
9) How does one know whether the design is good or needs improvement?
10) What are the detailed steps in designing a frame from start to finish?
11) What are the formal tests the frame is tested for?

Study results

WMP's core design activities and the time taken for each activity can be concisely summarized as follows:

1. Product specification: 2 days
2. Determine overall size: Half a day (0.5 day)

3. Design the base of the crate: 4 days
4. Design for loading and unloading of the vehicle : 2 days
5. Design for storage: 1 day
6. Finalize and document the design using Solidworks^{TM}: 2 days

Product specification

The fishbone diagram shown in Figure 2 illustrates how various information provided by the customer to WMP combines to form the customer inputs. All of the below inputs help in establishing the preliminary design specification. In most cases, the customer supplies the actual vehicle for which the frame has to be designed rather than any drawings or electronic CAD models. In the absence of the actual vehicle itself, the customer provides the dimensions of an imaginary envelope that encompasses the vehicle. The customer also provides WMP with information regarding fork lifting conditions, mode of loading and unloading the crate with vehicle at various warehouses, number of stacks of vehicle during storage and mode of transportation of the vehicles from OEM to the dealers and warehouses. All the above information forms the initial customer inputs to WMP to start building concept frames. These also form the high level customer requirements that the finished product must meet. The customer does not explicitly give a list of requirements that the product must meet, but the frame designer must extract the requirements that are trapped in the initial inputs provided by the customer.

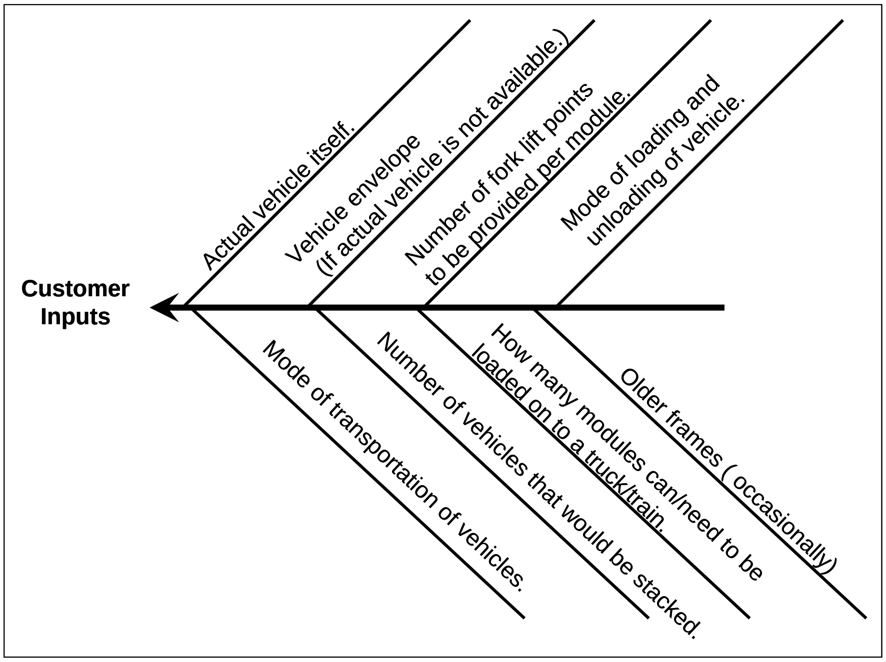


Figure 2: Customer inputs

The design specifications are determined from the customer inputs. The design specifications are specific details derived from preliminary customer inputs. The customer inputs shown in Figure 2 are mostly in the form of description and lack numerical values and details. The frame designer extracts useful information from the customer inputs that would enable the designer to arrive at an initial frame configuration if there are sufficient details. For example, consider the customer input “The actual vehicle”. The frame designer measures the overall dimensions of the vehicle and derives the outer dimensions of the frame to be designed, measures the width of the wheel to decide the additional members that might be needed to hold the wheels in place. The designer, based on the mode of loading and unloading the vehicle onto the crate is able to decide what part of the frame needs to be collapsible. Figure 3 shows a few design specifications that the frame designer derives from the customer inputs. Design specification need not necessarily mean only numerical values like weight and dimensions but also could contain specific design features that the designer might include to address specific customer inputs. These design specifications form the detail inputs for the frame design. For example, the designer needs to arrive at the dimensions of an imaginary box or envelope that would completely encompass the vehicle and is different for different kind of vehicles. Envelope dimensions are always given by the customer in the form of the actual vehicle and are an important design specification in deciding the overall size of the crate. The design specifications derived at this level, coupled with the frame designer's product expertise, are the basis to start designing the frame. WMP does not follow any formal templates, checklists, or other design tools to record the customer requirement and the derived design specifications. Informal ways are followed to record and keep track of customer requirements and design specifications. No formal tracking of the various main tasks and subtasks that need to be carried out nor the time spent on each task is recorded using design tools. The main document that would have information of customer requirements is in the form of "Memo" signed off by one of the frame designers. The frame designer typically takes about 2 days to derive the design specifications from the customer inputs. However, this depends on the type of vehicle for which the frame is to be designed.

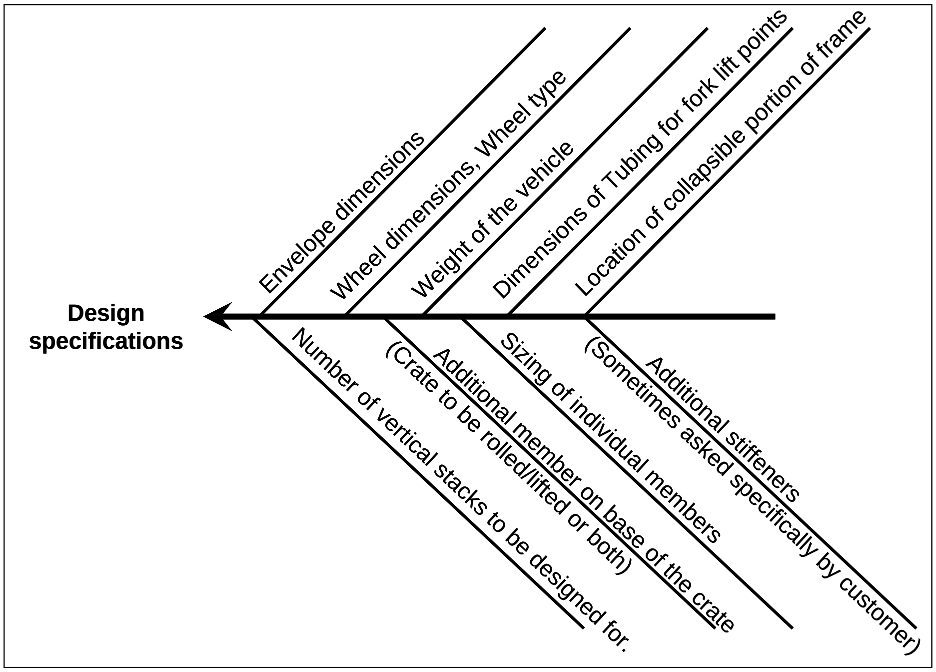


Figure 3: Design Specifications Derived from Customer inputs

Determining overall size

The first step in the design activity is to determine the outside dimensions of the crate. The preferred design will minimize the envelope dimensions of the crate. The crates along with the vehicle are shipped by ground transportation. The mode of transportation could be by road or by train. Each of these modes of transportation has its own limitation in terms of trailer or coach dimensions. Depending on the size of the vehicle for which a crate is being designed, the number of vehicles that can be shipped in a single container needs to be maximized. The envelope dimensions of the crate are a crucial factor in deciding the number of vehicles that could be shipped in a single container and thus the shipping cost for the customer. At this stage, the frame designer needs to be careful in choosing dimensions of the tubes that form the outer skeleton structure of the frame. The widths of these tubes add to the envelope dimensions and decide the overall size of the crate.

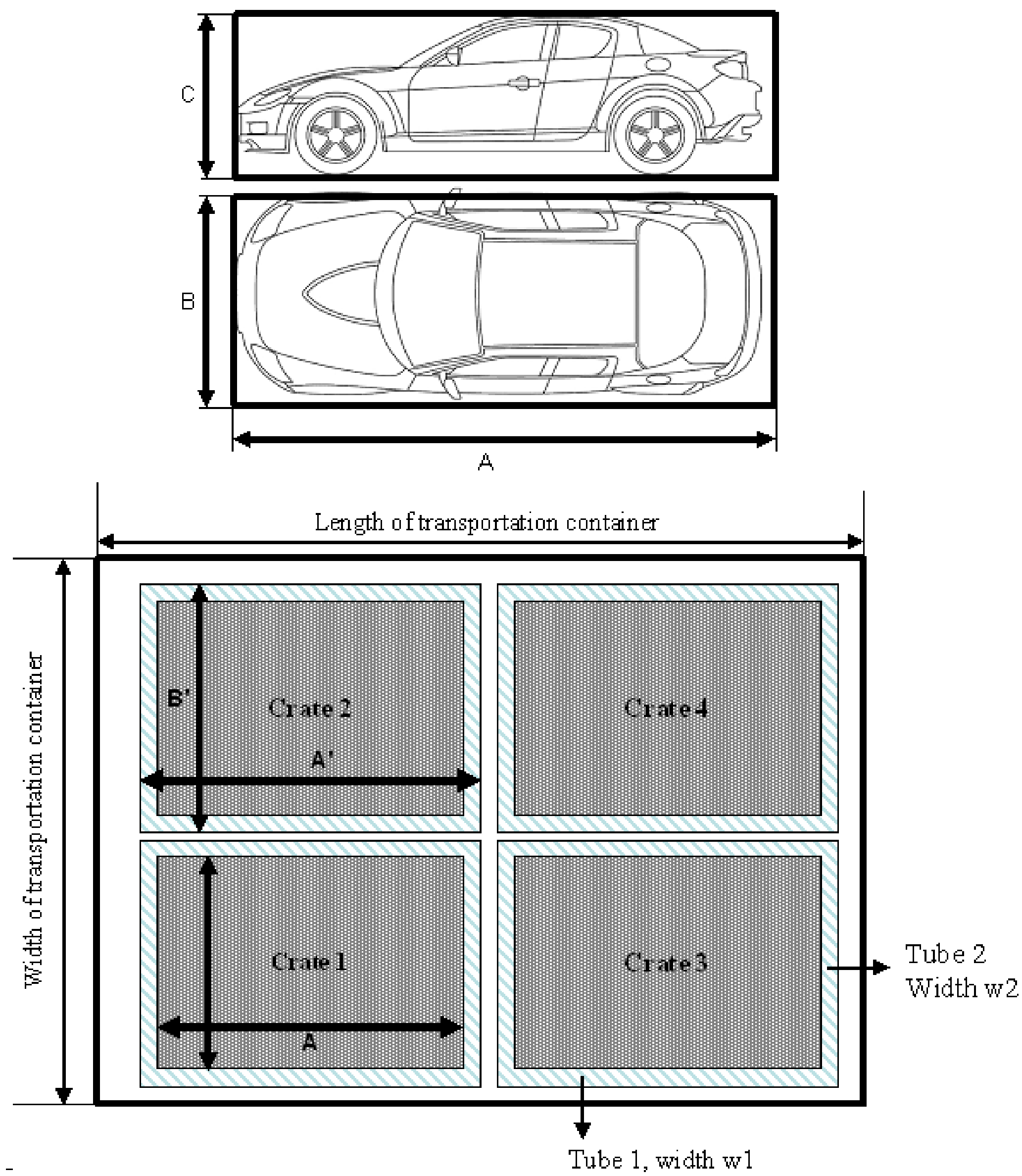


Figure 4: Envelope dimensions and crates placed in a transportation container

Figure 4 illustrates the envelope dimensions, its relationship to the skeletal tube dimensions and container dimensions. The dimension "A" "B" and "C" are the envelope dimensions of the vehicle for which a crate is being designed. Dimensions A, B, and C correspond to the length, width, and height of the envelope that encompasses the vehicle. The skeletal crate is made of two pairs of tubing of width w1 and w2. The envelope dimensions of the crate are as follows

A' = A+2*w2

B' = B+2*w1

The frame designer knows the length and width of the transportation container from the design specification. Let N1 be the number of crates to be placed along the width and N2 be the number of crates to be placed along the length of the container. Now the designer has to decide the width w1 and w2 of the tubing such that

Width of container >(N1* B')+Clearance

Length of container > (N2* A') + Clearance

A similar calculation is performed for the height of the crate (not shown here for clarity). There is no specific value for the clearance, but the frame designer would choose an appropriate clearance such that there is no tight fit between the container and the crates. The frame designer must choose appropriate values of w1 ,w2 and clearance such that N1 and N2 can be maximized for a given transportation container. If a large value of w1 is chosen, N1 may become 1. This means that there would be large volume of empty space in the container resulting in increased transportation cost for WMP's customer. Furthermore, the vehicles to be transported may have additional components that need to be packaged separately but enclosed within the crate. For example, riding lawn mowers may have safety frames, removable mowers, or external batteries. These additional components are commonly mounted either underneath or to the rear of the vehicle while loading. This mounting feature is designed such that these components do not damage the vehicle nor sustain damage while loading and unloading the vehicle. The envelope is primarily based on the type of the vehicle that is being transported. If WMP is designing a frame to transport non-wheeled vehicles such as jet skis, the frame must be designed such that the vehicle is in a fixed position and locking mechanisms are implemented to hold the vehicle in place. However, such information or special requirements are available to the designer at the very beginning of the design cycle and would be included in the design specifications. All of the above factors that need to be considered and the process followed while determining the overall size of the crate are depicted by the flow chart shown in Figure 5. The frame designer takes approximately half a day to determine the envelope dimensions and arrive at the overall size of the crate.

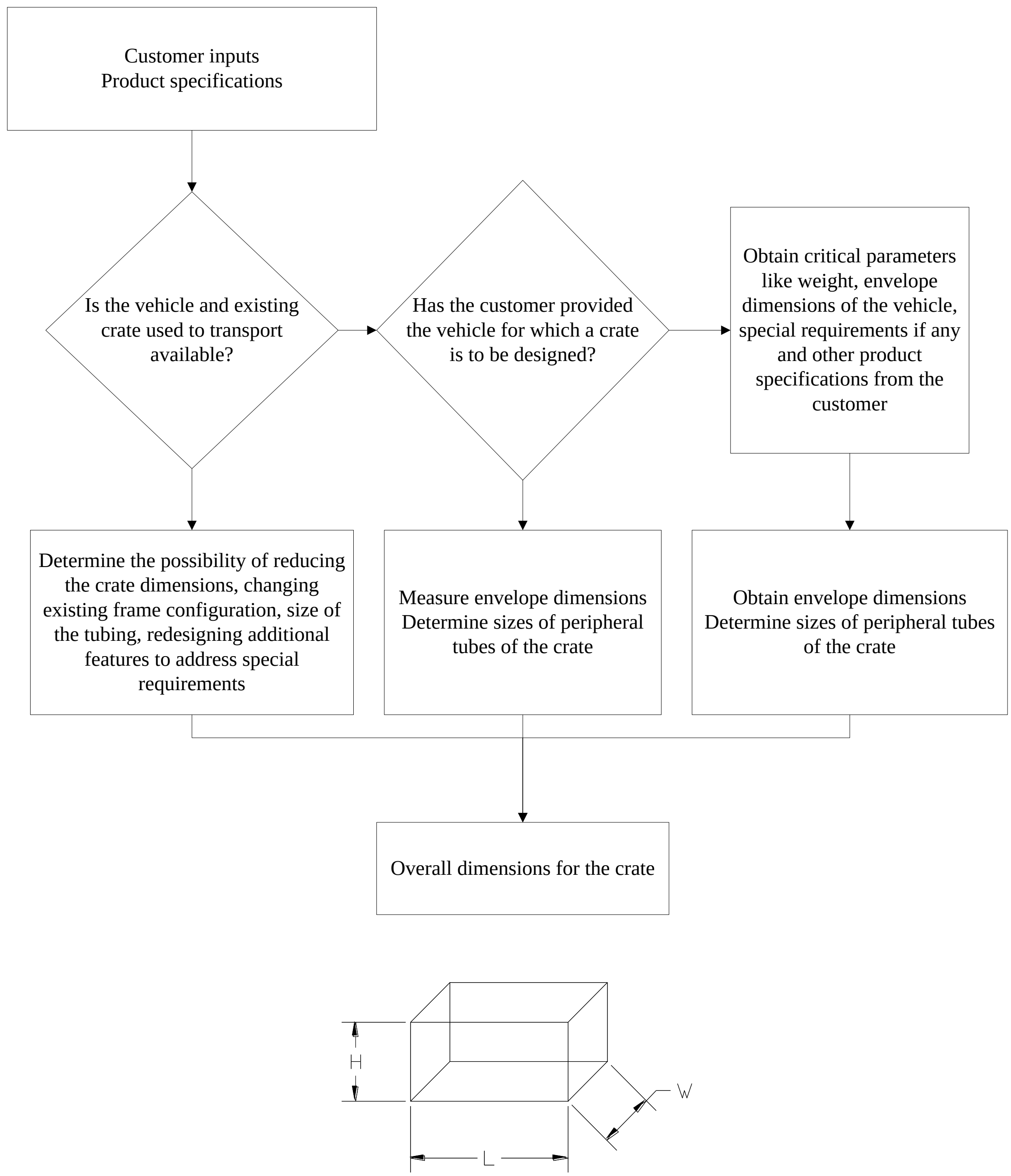


Figure 5: Determining Overall Size/dimensions of the crate

Designing the base of the crate

Designing the base of any crate is one of the most important activities in the crate design cycle. The base carries the entire load of the vehicle. The sizing of the tube and arriving at a frame configuration to transport and store the vehicle safely are the primary tasks of frame design. After the overall size is determined, the base of the crate is designed to accomplish the following: (1) permit ease of loading/unloading, (2) provide forklift access and prevent improper forklift usage, (3) allow stacking, and (4) carry the load of the vehicle without excessive deformation. The process of designing the base of the crate is detailed in the flowcharts shown in Figure 6 to Figure 8.

At this stage, the frame designer has design specifications and overall crate dimension to start designing and building a prototype frame. To start with, the base of the crate would depend on the type of vehicle that the base is being designed for. For non-wheeled vehicles like Jet Ski, there needs to be holding mechanisms attached to the base of the crate. If it is wheeled vehicle, additional tracks are to be provided if the front wheel diameter is small. In such situations, the vehicle will be loaded onto the crate by reversing it into position because there is no steering wheel provided to control the front wheels. However, such information is available at the start of the design process in the form of the vehicle itself and the design specifications. Figure 6 illustrates the above part of the base crate design.

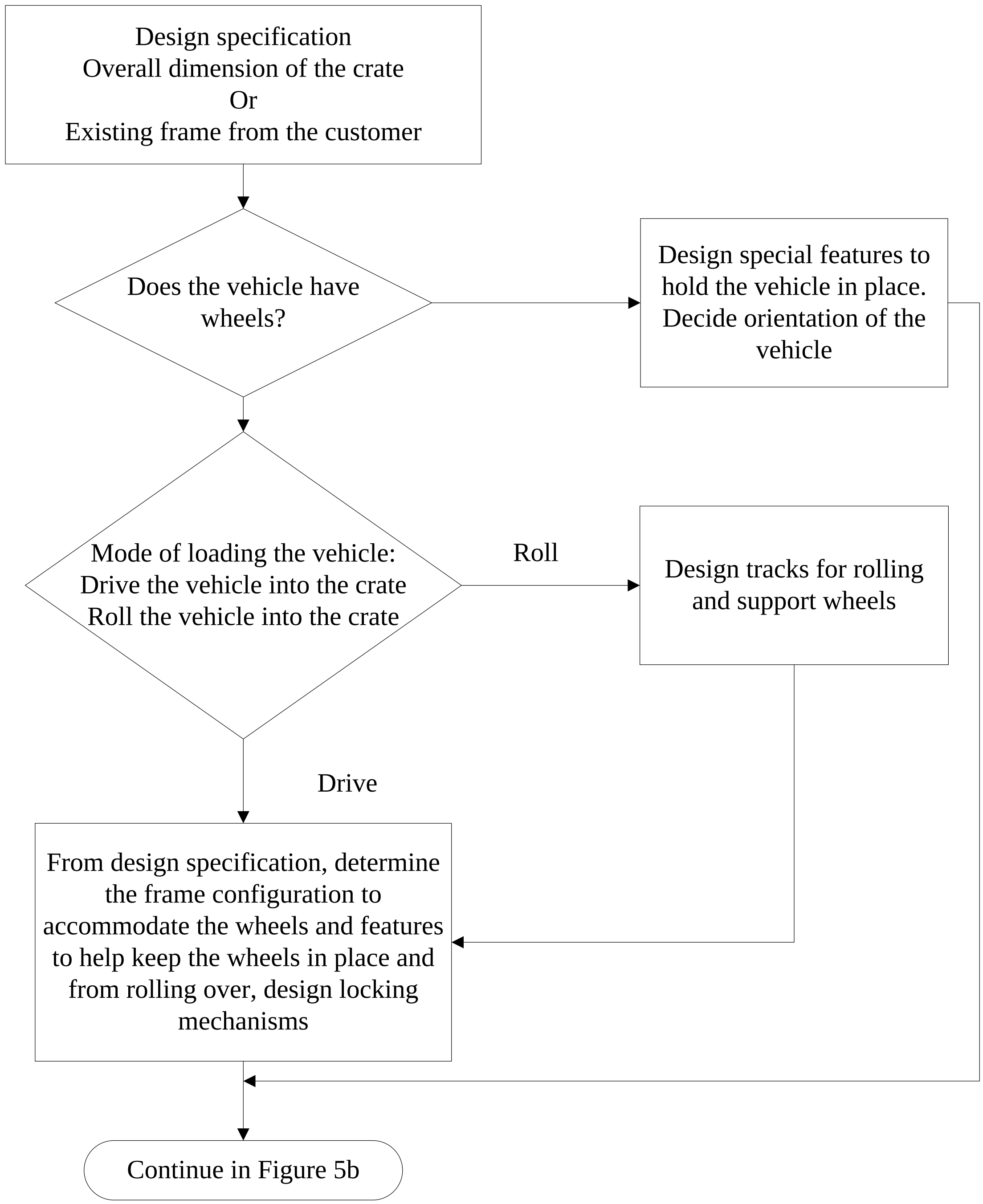


Figure 6: Designing the Base of the Packaging Frame (Part A)

All the crates with vehicle are stacked during storage and transportation. Stacking cups need to be included in each of the base frame design. The design of the stacking cups does not change with each design and are common to all frame designs. The next important task in designing the base of a crate is to decide forklift points and design features to assist forklift of the crate along with vehicle. Forklift points are decided based on the center of gravity of the vehicle. Forklift points need to be provided close to the CG of the vehicle in order to reduce the effect of moment caused due to weight of the vehicle. A crate designed for forklift access points from all the four sides of the crate would result in larger tube sizes and increased cost. Most of the crates are designed for forklift access from two sides. Once the forklift access points are decided, the frame designers need to arrive at a base configuration such that the crate would not topple when lifted using a forklift. Tubes whose cross-section dimensions are greater than those of the forks could be used so that the forks slide into these tubes while lifting the crate. Such a design would ensure that the crate would not topple or slide during forklift operation. These tubes also act as structural cross members of the frame contributing to the stiffness of the structure. Various error proofing techniques are built in to the base crate design to prevent damage to the vehicle due to improper use of the forklifts. Stoppers are placed at specific locations to ensure that the forklift does not overshoot and cause damage to certain parts of the vehicle. Stoppers are also placed at the sides of the crate that are not intended for lifting. Figure 7 illustrates the above discussed steps in designing the base frame. The initial design decisions on cross section of members, fork lift points, and the number of vertical and horizontal members required to support the load of the vehicle without significant deformation are solely determined by the experience of the frame designers. The basis for decisions on initial frame configuration, tube sizing, and special features is from lessons learned from past designs. These lessons learned are by means of trial and error. The frame designer, based on his experience of building numerous frames over the years, would avoid certain mistakes that would have committed in some of the earlier designs. The designer would also know the frames that passed the load tests and resulted in acceptable deformations and with no field problems. However, if the customer provides the currently used frame design, the designers can commence with a baseline. The provided baseline may be a successful or a failed design. In this context, successful would mean that the frame is serving its design intent without failure and in such cases the customer would clearly mention the reason why a new frame design is required. The reason could be cost. Significant modifications in the vehicle being transported which may call for a partial redesign of the crate. A failed design would give valuable insight to the designers in terms of design flaws in the existing design so that they do not repeat the mistake. However, the frame designer still follows the same steps in base frame design without a baseline. A baseline would only reduce the time taken for designing a frame from scratch. With a baseline, the designer would have an initial frame configuration to start with and may need to only modify certain features to obtain a new frame design. Once the frame designer arrives at a frame configuration and tube sizes, a preliminary physical prototype is built. The frame designers typically take about one week to complete the design the base of the crate and running through crude tests until they arrive at a satisfactory frame configuration.

Prototypes can be either physical hardware or they may be computational simulations of product performance done on a computer [Dixon and Poli]

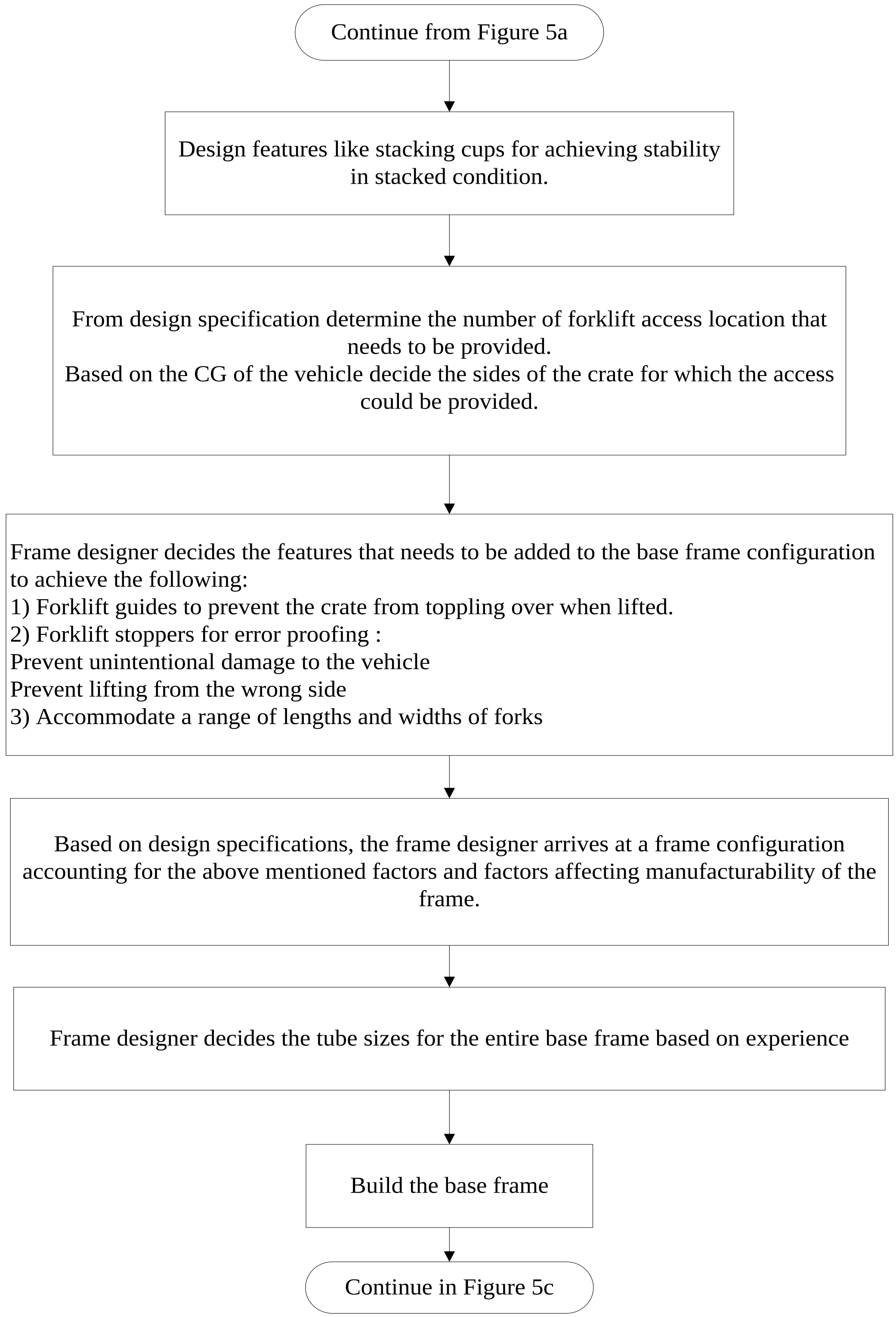


Figure 7: Designing the Base of the Packaging Frame (Part B)

A physical prototype is a simplification of a product concept. It is tested under certain range of conditions to approximate the performance and is ultimately used to make product development decisions with high confidence and reduced risks [Otto and wood].

Once the physical prototype is built, the prototype base frame is then tested for certain loading conditions to check for deflection and stability. Preliminary testing is carried out by placing the vehicle to be transported on the fabricated base and then lifting using a forklift. The frame is then visually inspected for any bending or stability issues. Visual inspection during the tests forms the basis for adding additional members and/or changing tube gauges to arrive at a satisfactory design. A satisfactory design would be restricting the maximum deflection to within ¾ inch. The preliminary testing also helps in checking the functioning of other features like locking mechanisms and error proofing features included for various reasons as discussed in Figure 7. After the preliminary testing, the frame designer may include additional features to address the problems with the frame that might not have been overlooked during product specification stage. More significantly, the visual inspection is considered an “art” internal to WMP accomplished by the frame designers. This “art” being designer specific and, in an event that the frame designer quits or retires from WMP, the “art” of visual inspection and arriving at a solution to address the problems found during visual inspection is lost. A new designer, due to lack of experience may not able to detect the design flaws associated with the frame design and would result in increased design cycle time, over designed frame, increased product cost, and lower customer satisfaction.

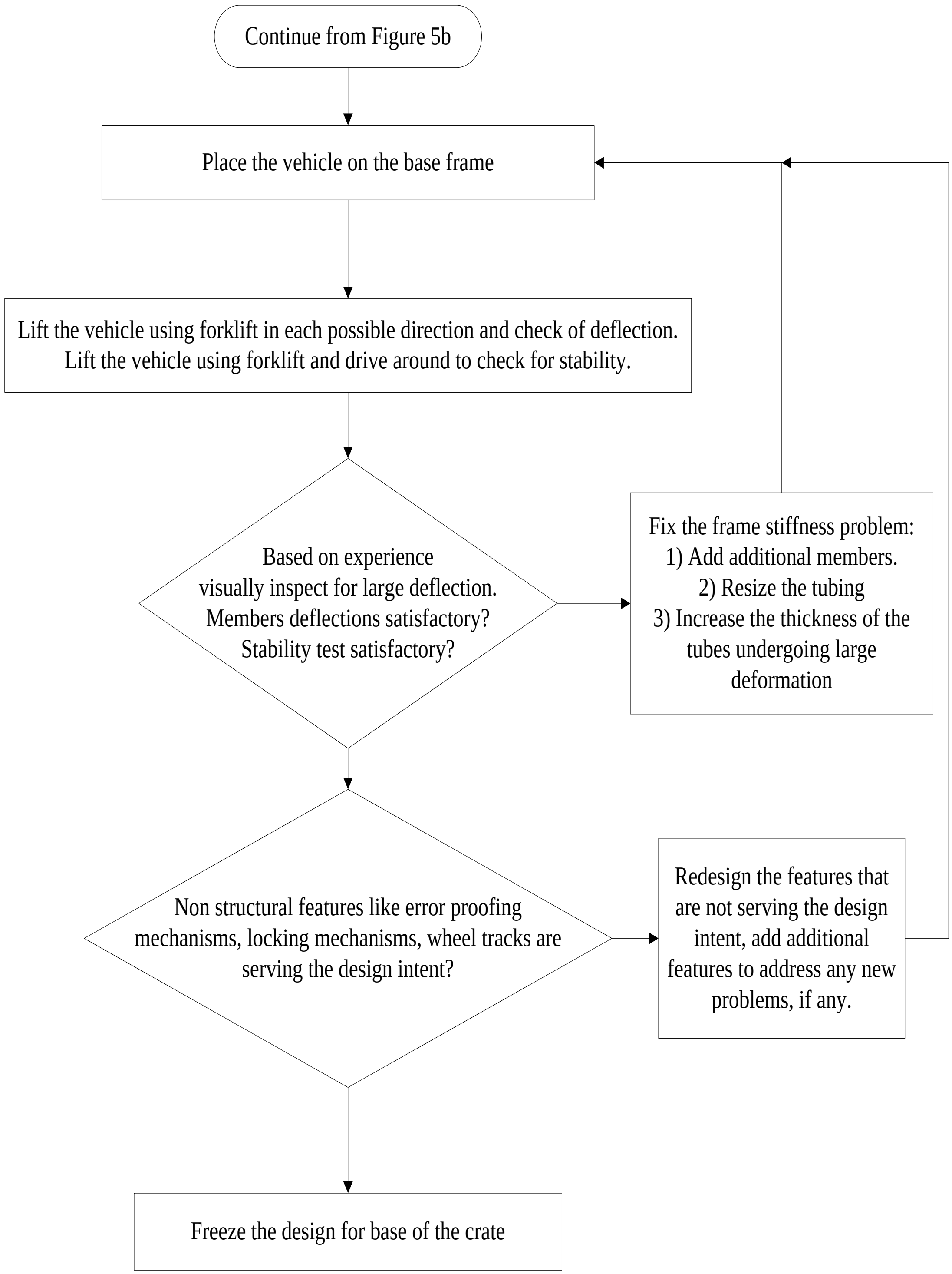


Figure 8: Designing the Base of the Packaging Frame (Part C)

Design for loading and unloading of vehicle

The management reported that a majority of crates designed by WMP are built for transporting wheeled vehicles. These vehicles are unloaded at local dealers with minimal material handling equipment. Therefore, the objective of this step is to design for ease of loading and unloading of vehicles. The crates are designed such that there would be no damage to the vehicle while loading and unloading at the dealer warehouse or during storage. Damage can result from instability, improper forklift usage, and loosely kept additional components, which may damage other parts of the vehicle. Damage could also result from the above factors coupled with transportation. The crates and the vehicle may move substantially during transportation resulting in damage due to rubbing of parts, collision of parts and the parts falling of during loading and unloading of the crates. Figure 10 illustrates the process and the factors that are considered while designing the frame for ease of loading and unloading the vehicle.

If the vehicle has wheels, it would be driven into the crate. If the front or rear wheels are small, tracks need to be designed for the base of the crate. The tracks are sheet metal panels that run through the length of the crate and are placed over the cross-members. If the vehicle is to be hoisted in and out of the crate, as in the case of a Jet ski, the top frame needs to be removable. If the vehicle is to be driven in and out of the frame, the sides of the frame should be collapsible. The vertical members of the frame are usually collapsible. The assembly of the frame would be done as follows. The base frame has tubing at the four corners. This tubing acts as a female part for assembly mating condition. Then the vertical members are placed into it. The top frame too has female parts at the four corners and is then placed over the vertical members to complete the assembly. Figure 9 shows a sample assembled frame. If the vertical members are not designed to be collapsible, then a hinge mechanism needs to provided such that the vertical members can be lowered at the time of loading and unloading the vehicle.

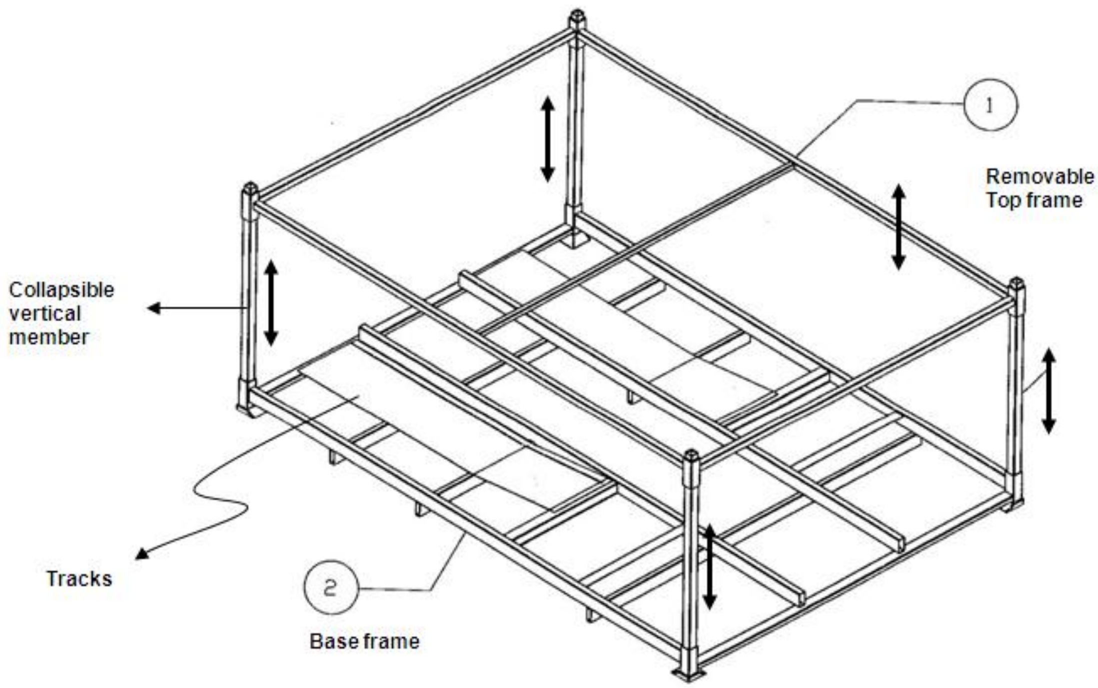


Figure 9: A sample assembled frame showing the collapsible components of the frame.

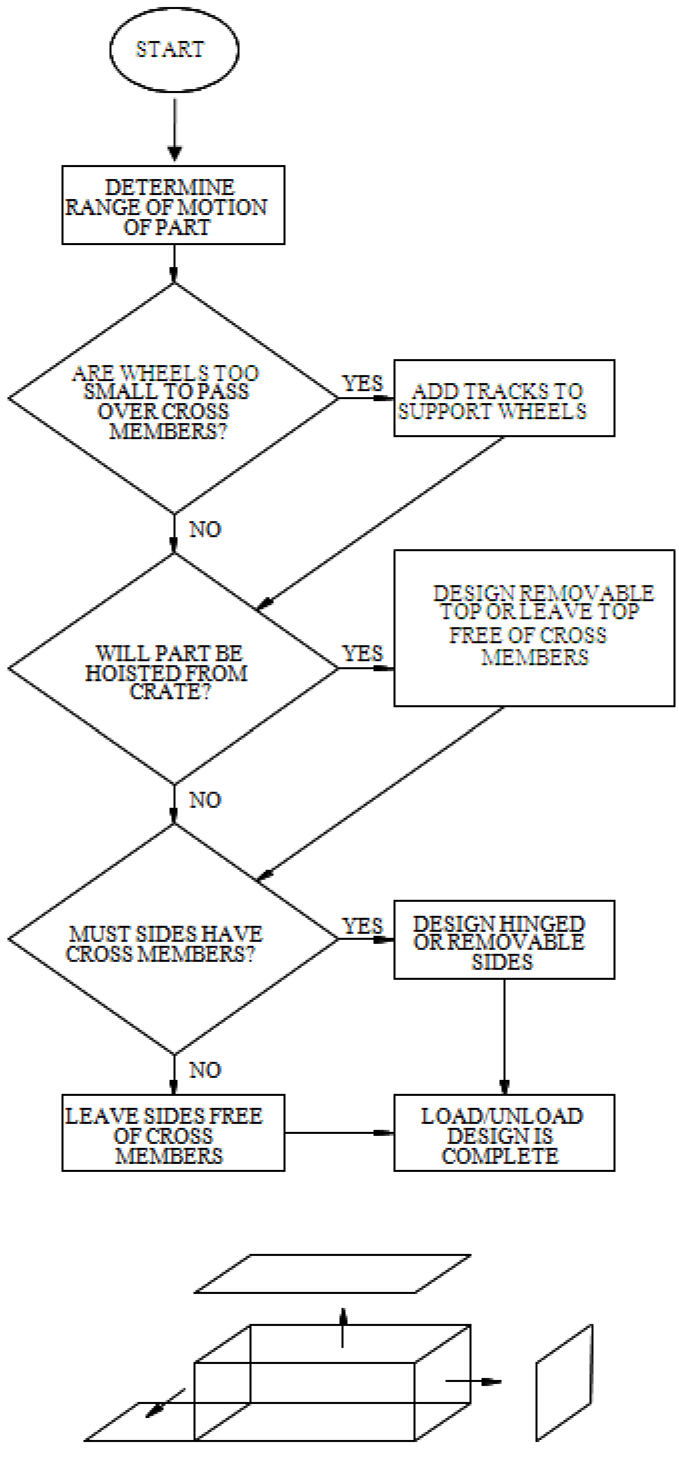


Figure 10: Design for Loading/Unloading Vehicle

Design for storage

Depending on the layout of the customer's warehouse, crates may be stacked up to six units high. However, since the reaction points of the vertical loads in stacking condition will be the four corners of the crate, the number of stacks while storing does not put any additional loading requirement on the base of the crate. The stacking condition affects the loading requirements on the vertical members of the crates. The stacking condition could result in buckling of the vertical members. The chances of buckling would increase if there is a misalignment from crate to crate while stacking. This would make the vertical loads eccentric and increase the chances of buckling. To prevent misalignment during stacking, a feature to register one crate to another must be included in the design. This is accomplished by welding female cups on the four corners of the crate top and male bosses on the four corners of the base as shown in Figure 11. Furthermore, the crates may move a lot during transportation and the designer must ensure that the vertical members do not slip out of position. The depth of the cups to be used is based on experience, trial and error, and past failures.

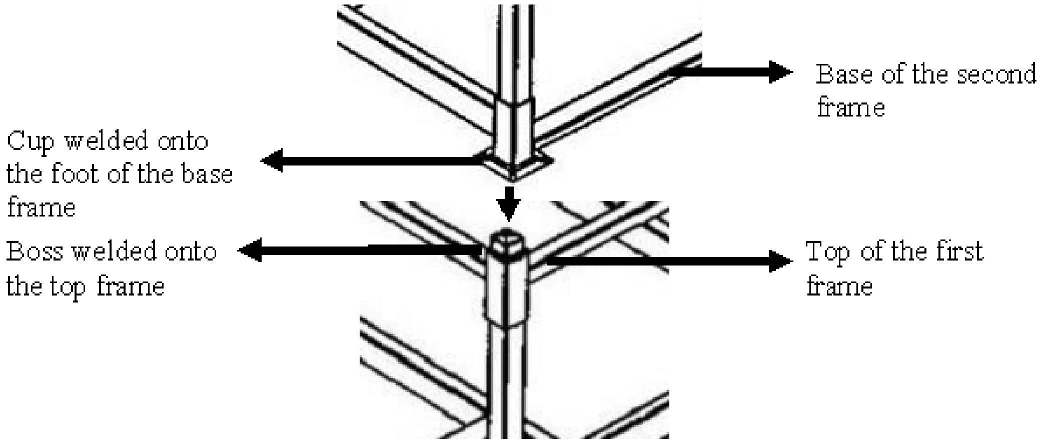


Figure 11: Female Cup and Male Boss Features of the Frame during stacking

Figure 12 depicts the process of designing the crates for storage requirements. The storage requirements are obtained from the design specification derived from the customer inputs. Based on experience and the number of stacks the customer specifies, the frame designer may choose to include additional cross-members on the sides of the crate to improve stiffness in the vertical direction. There are no tests conducted at WMP for the stacking condition, but the crate is put to test directly at the customer's location. For this reason, the frame designer may over design the vertical members of the crate so that there is no possibility of failure when the crates are stacked at the customer's storage facility.

During stacking, the boss sits inside the cup. The cup ensures that the base of the frame does not slip while being transported and also reduces eccentricity due to misalignment of the frames during stacking.

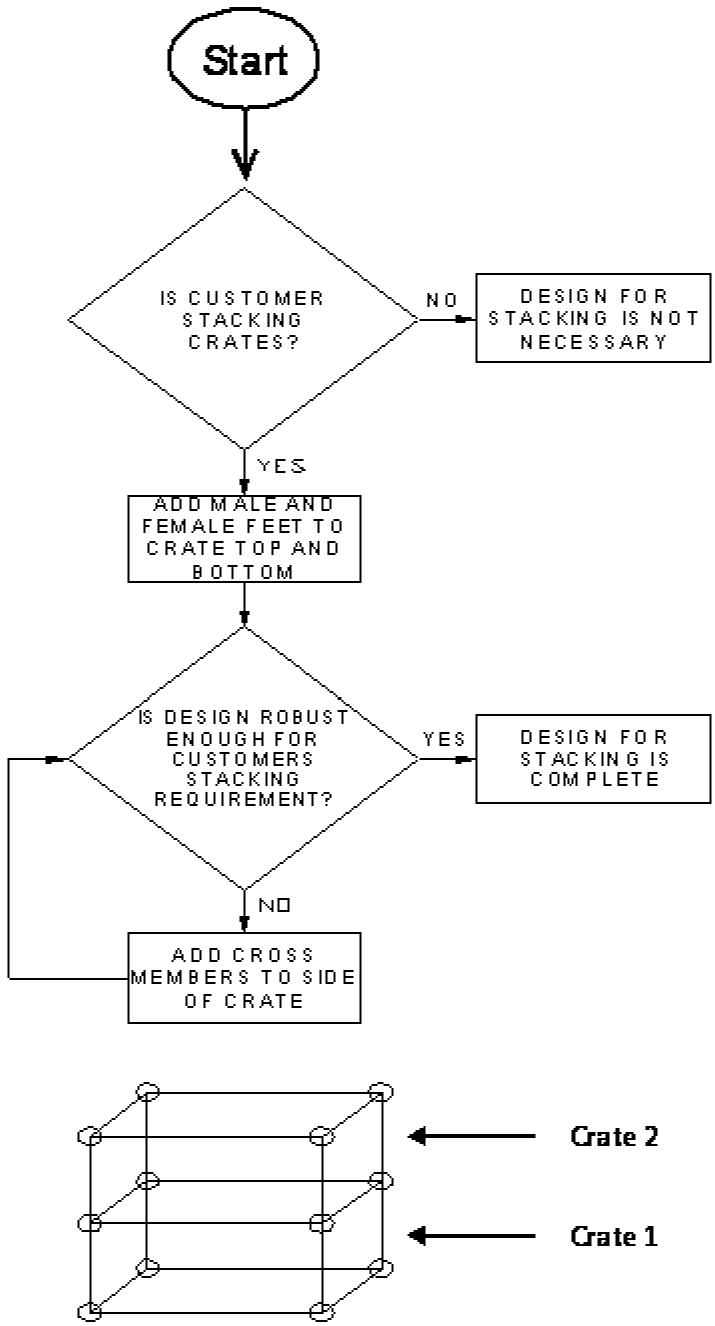


Figure 12: Design for Storage

Finalizing the design

After the aforementioned design decisions have been made, as many as five different prototype crates are built. However, the frame configurations of various prototypes are similar and have a few minor modifications. The difference would be in tube sizes and additional features to address specific customer requirements. Building these prototypes typically takes 7 to 10 days. Once all the prototypes are ready, the management comprising two members along with the frame designers then choose a final design based on examination of the design features and whether or not the frame meets the customer requirements that are recorded in the form of the memo created by the frame designer at the beginning of the design cycle. The chosen design is then subjected to a series of formal tests. The formal tests are carried out by the customer. The formal tests include a shake test and road test with the loaded vehicle. The customer then gives feedback to WMP that is mostly descriptive rather than quantitative. The results would illustrate the regions of failure, regions that need modification to address any problems that showed up during the tests and suggestions to reduce costs by eliminating certain members. If results of tests are acceptable, the design is documented in Solidworks™. It is at this stage that the product costing is done and quoted to the customer. The total time taken for product development amounts to a minimum of 12-15 days and may increase if the customer changes any requirements during or at the end of the design cycle. The material cost for prototyping would not be a significant factor, as WMP is building only a few prototypes to finalize the frame design. The most significant cost element is the price of steel. WMP would cost the frame, accounting for the steel prices, manufacturing costs, and a profit margin. A significant amount of physical resources, approximately 25-30 man-days, have been invested in designing and prototyping the frames that are shipped to the customer. If the customer chooses to purchase crates from WMP, welding jigs are constructed for ease of manufacturing. There are no fixtures built while prototyping. To build the jigs for mass production, the frame designer places parts of the frame and builds a fixture around the prototype and then finally removes the prototype. Figure 13 illustrates the above discussed procedure for finalizing the crate design.

From the formal tests, WMP knows whether or not the designed product meets the customer requirements. However, WMP still does not know the stress levels in the members, whether the frame cross-sections are optimized, the factor of safety of the frame, and whether the current arrangement is the most optimum arrangement of the members to carry the load of the vehicle. All of the above are very important factors in frame design. The critique of the current design process followed at WMP and possible improvements is presented in Chapter 3.

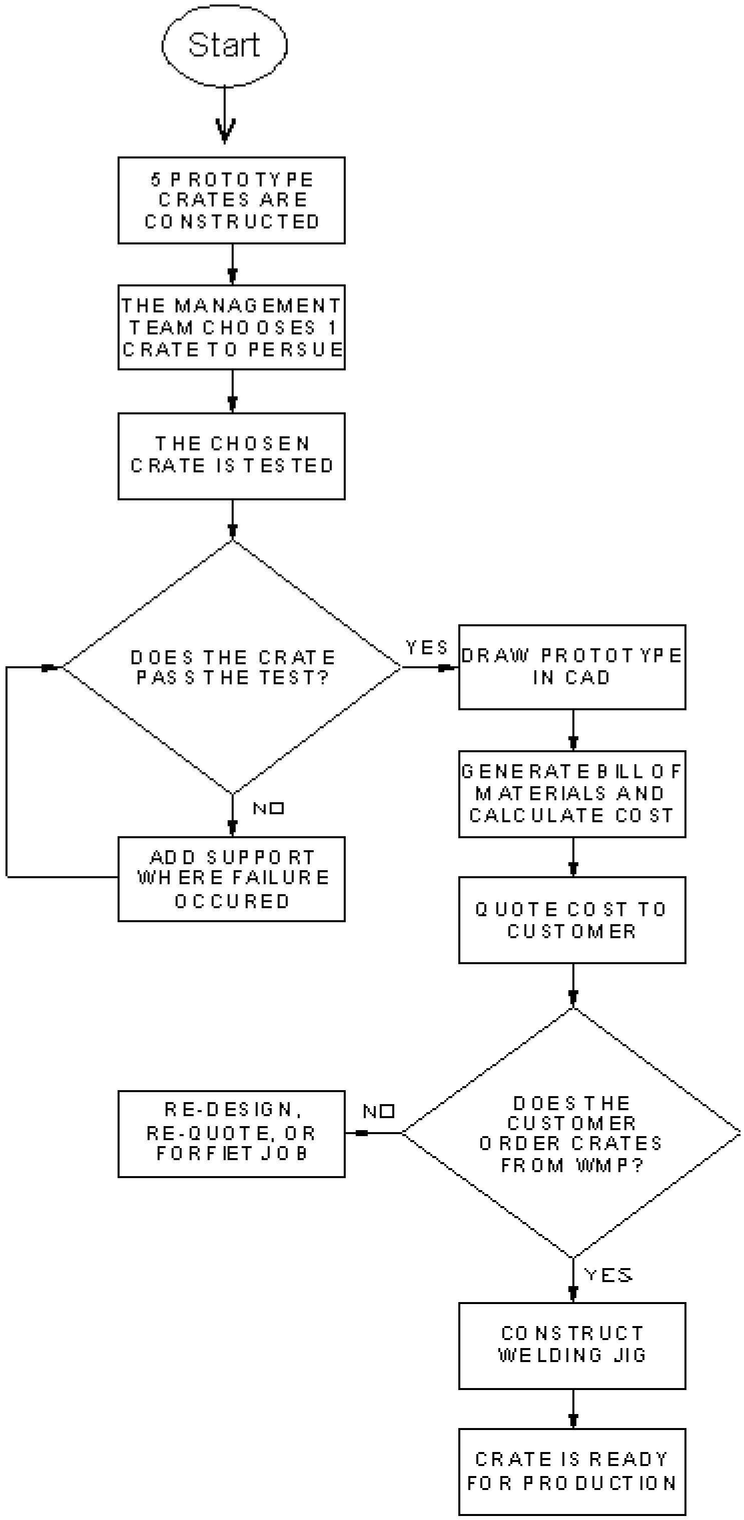


Figure 13: Finalize Design and Prepare for Production

CHAPTER 3

DESIGN PROCESS

Systematic approach

Due to the variety of problems and tasks in the development of technical products, design activities are many sided. First of all, they rely on basic scientific and engineering knowledge, but also on special experience in the specific product area. The activities cannot be forced into rigid organizational or procedural templates. [Pahl and Beitz].

Most of the time, the design process heavily depends on experience in specific product area and do not follow a systematic approach, and are often carried out too quickly leading to unforeseen consequences. The deliberate step-by-step procedure, on the other hand, ensures that nothing essential has been overlooked or ignored, and is therefore indispensable while designing a product. In the case of adaptive designs, it is possible to resort to time-tested approaches and a step-by-step procedure for where it offers special benefits. If designers are expected to produce better results, then they must be given the extra time the systematic approach demands, though experience has shown that only a little extra time is needed for a stepwise procedure and scheduling becomes more accurate if the step-by-step method is followed rigorously. [Pahl and Beitz]

According to Pahl and Beitz, the design process can be divided into four main phases: task clarification, conceptual design, embodiment design, and detailed design [Pahl and Beitz]. These four phases are the most general phases in design and are found in most textbooks on design. The wording of these four phases may vary from book to book but the tasks performed in each of the phase remain the same. Some authors subdivide the phases resulting in five or six phases, but again the tasks associated remain almost the same. Therefore, following any of the systematic design procedures illustrated in most of the engineering design text books would result in an improved design process.

Engineering conceptual design, configuration design of parts, parametric design and detail design are the four phases described by Dixon and Poli in their text book [Dixon and Poli]. These four phases are almost the same as the phases described by Pahl and Beitz. Ulrich and Eppinger propose the following five phases of design, Concept development, System level design, Detail design, Testing and refinement, Production ramp up [Ulrich and Eppinger]. These five phases cover all the tasks that are described in the Pahl and Beitz design process. Identifying customer needs is included in the concept development phase. System level design is essentially embodiment design and detail design includes final design, documentation, and design for manufacturing. The testing and refinement phases and production are illustrated as separate phases, while Pahl and Beitz have it included in embodiment and detail design.

The following are brief descriptions of the four phases illustrated in Pahl and Beitz.

1) Task Clarification: The first step in product development is to clarify the task in hand. It is important to have details of the requirements that the final product has to satisfy to meet the market and customer needs. The clarification of the task is to collect information about customer specific requirements and general requirements like safety standards, ergonomics, production, assembly, transportation, operation, and maintenance constraints

that have to be fulfilled by the product. Most organizations have a formal requirements list for the product that they develop and these requirements lists form an important document that is updated continuously and the subsequent phases of the design should be based on this document. When preparing the detailed requirements list it is essential to state whether individual items are demands or wishes. Demands are requirements that must be met under all circumstances, wishes are requirements that should be taken into consideration if possible. The following method could be adopted to compile a requirements list.

a. Identify requirements:
    - Demark quantitative and qualitative data.
    - Specify demands and wishes clearly.
    - Rank wishes according to importance.
    - Collect further information if necessary.
b. Arrange the requirements in a clear order: Define the main objective and main characteristics, identify subsystems, functions, assemblies.
c. Record amendments if any.

2) Conceptual design: The conceptual design phase determines a concept or working principle that may partially or fully satisfy the requirements list. This is achieved by establishing function structures, searching for suitable working principles, studying previously solved similar problems. This phase also

involves preliminary material selection, rough sketches and dimensional layout, simple prototypes to demonstrate the concepts. The solution variants thus obtained must be evaluated using specific criteria and the best solution concepts can be selected for further scrutiny in the embodiment phase. In their search for optimum solutions, designers are influenced by fixed or conventional ideas. To solve the problem of fixation and sticking with conventional ideas, abstraction is used. The design tools such as function structures, working structures, and combining working principles to achieve product functionality goals are well illustrated in most design text books. These tools can be used to develop concepts and solution variants. Appropriate evaluation criteria must be used to rank the concepts. Evaluation criteria are derived from the requirements list and general technical and economic characteristics of the product that is being designed.

3) Embodiment design: In this part of the design process, starting from the working structures or concept variants of the product, the design is developed accounting for finer details like spatial compatibility, technical evaluation, shapes, and material of the components. It is this phase of design which calls for calculations ranging from simple hand calculations to complex simulations using finite element methods to establish technical competency of the product that is being designed. In the process of elaboration of embodiment designs, many details have to be clarified, modified, analyzed and optimized.

4) Detail design: In this phase of design, the final arrangement of parts, shapes, dimensions, tolerances, cost estimates, production drawings, all the materials and specific processes the material must undergo to obtain desired metallurgical properties are specified. The designers may need to change some aspects of the product even at this stage due to lack of understanding of some sub-function or lack of attention to detail. The final prototype is built at this stage that could be sent to the customer for final approval and be subjected to any customer specific formal tests. If the product fails the customer specific formal test, the designer still has time to carry out some minor modification to the final design to address the problems without affecting other aspects of product design. It is at this stage, all the manufacturing details and processes are defined for mass production of the product. The components required to manufacture the product are either built in-house or outsourced.

The Figure 14 below describes the steps of a design process and the subtasks that need to be performed in each of the above mentioned design phases.

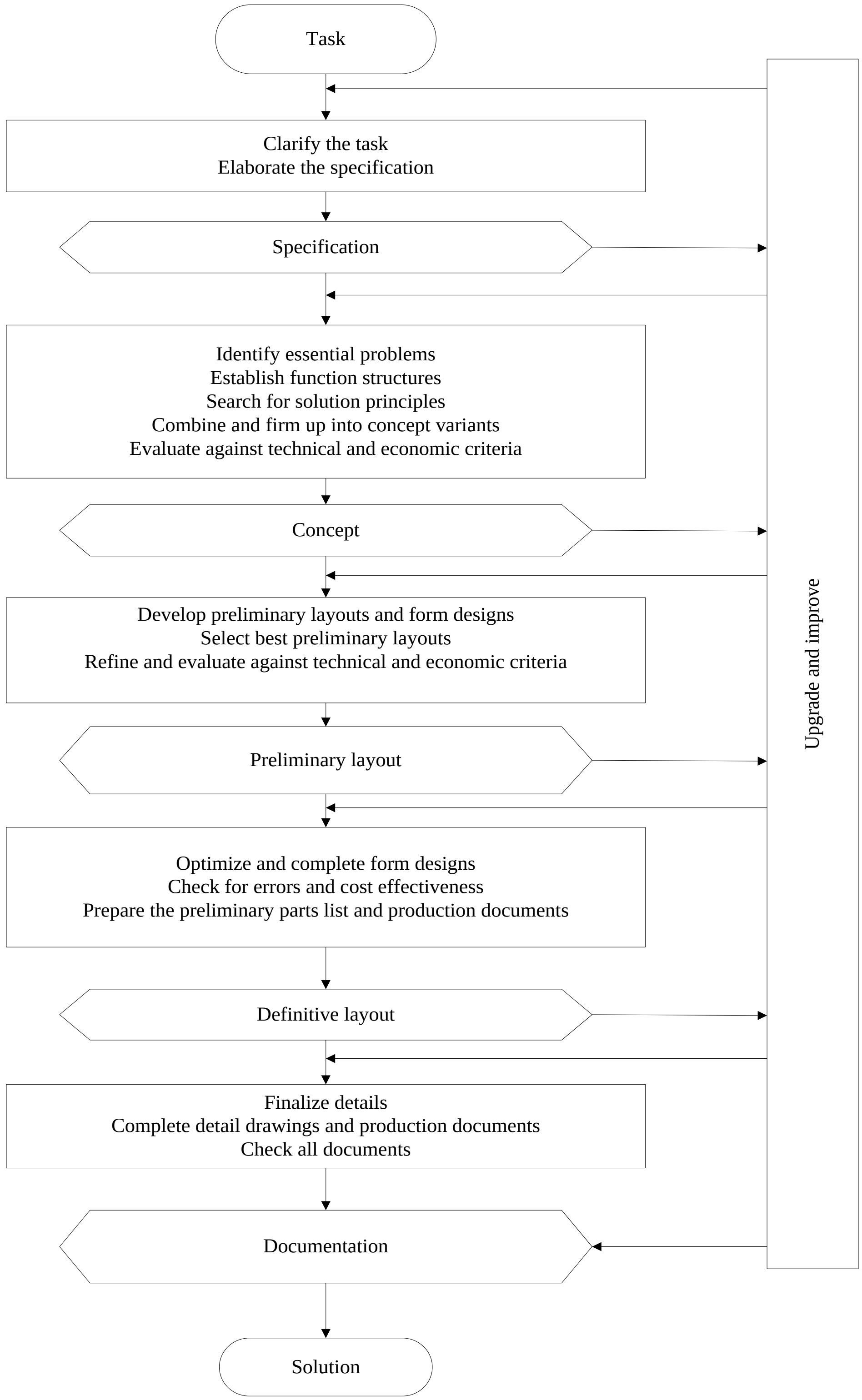


Figure 14: Pahl and Beitz design process [Pahl and Beitz]

The design process at WMP

The design process followed by WMP is summarized in Table 1. Activities involved are categorized into four general design stages, showing how they combine to form a "General approach to frame design" followed by WMP.

Table 1: Design Process of WMP

Task	Phases of systematic design	Time taken	Design tools used	Design tools that could be used
Customer inputs/order: Customer requirements. Preparing requirements list. Converting customer specifications to "Design specification"	Identifying customer need Establishing product specifications.	2 days	None	The requirements list
Concept generation: Identifying baseline - similar designs that has worked in the past. Identifying changes to be made based on new requirements. Choose frame member cross-sections. Based on past experience, identify locations needing additional structural reinforcement	Conceptual design Fabricating preliminary design	5 days	None	Virtual prototyping of concept Evaluation matrix Tool for searching principle solutions from design database Engineering simulation tools used to calculate deflection and stress.

Prototyping and testing: Testing: Load the actual vehicle on the frame and lift using a fork lift. Visually inspect for bending and possible weak members. Weld in additional members/change cross-sections/gauges based on preliminary testing. Build 3 to 5 different prototypes and select the best for production.	Embodiment design	3 days	None	Optimization tools. Checklists Documentation of best practices and lessons learnt
Detail design, Manufacturing frame, Jigs and fixtures: Build a 3D model of the frame using Solidworks with BOM & manufacturing details. Weld a set of members separately (Sub assemblies). Weld these sets to obtain the final assembly (finished product). Put the frame through formal tests	Detail design	2 days (Not including time taken for tests)	CAD package-Solidworks	Decision matrix Rules and guidelines for manufacturing Design report

The general stages involved in the design process at WMP can be broadly classified as

1) Identifying customer needs and establishing product specifications

2) Concept generation: Developing/fabricating preliminary design

3) Prototyping and testing

4) Detail design and manufacturing

The above design process can related to the Pahl and Bietz design process as shown in Table 1.

Figure 15 shows the current usage of tools and the role of experience at WMP for different stages of design. The current use of analytical tools in the design cycle is nonexistent and the product development heavily depends on experience and prototyping and the use of CAD tool is limited to the detail design stage for documenting the final design. Figure 16 shows where we want to be in terms of tools usage at WMP. An increased use of analytical and CAD tool throughout the design cycle coupled with implementation of other standard design tools like requirements checklists, evaluation matrix would reduce prototyping.

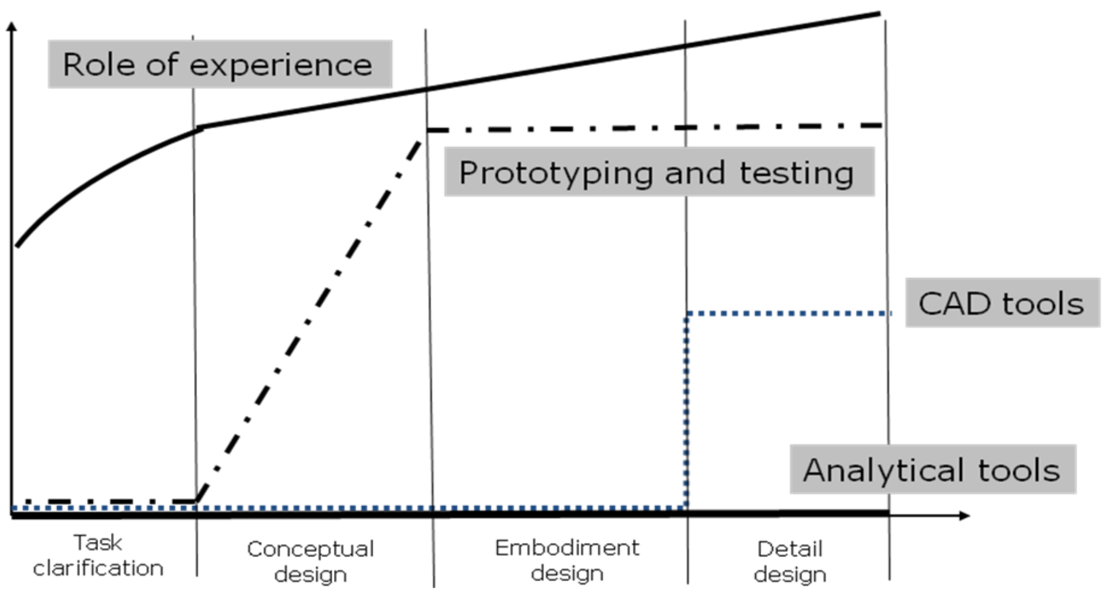


Figure 15: Use of various tools and the role of experience at different stages of design

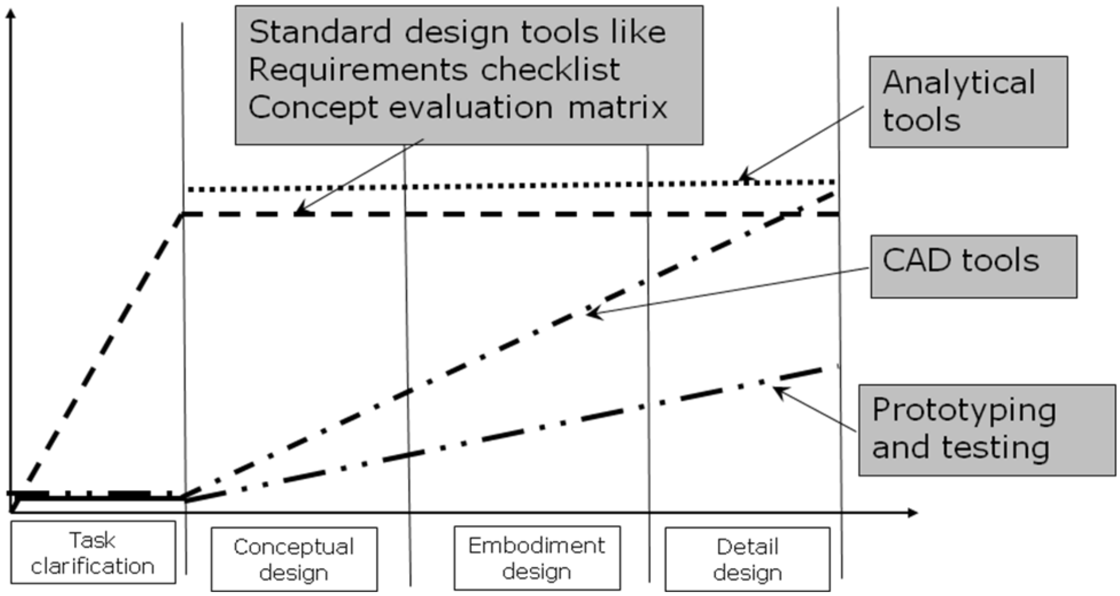


Figure 16: Projected tool usage-where we want to be.

<u>Critique and discussion of the design process</u>

This section critiques the different steps in the design process, identifying areas of potential improvement and enhancement through application of formal design methods and innovative design enablers. As described in Chapter 2, the "Design Enablers" are design tools that assist the designer at various phases of the design cycle. The design enabler could take any form, for example, it could be as simple as a requirements checklist or as complex as a computer based analysis tool.

Customer inputs

As discussed in Chapter 2 product specification and customer inputs are the first task in frame design followed at WMP. Currently the only way the customer inputs and the derived design specifications are captured in the form of a "memo" signed off by one of the frame designers.

The customer inputs/expectations are not captured in a formal manner before starting a design. If the customer inputs were captured in the form of a standardized checklist, the designer would be able to check on each of the expectations after completion of specific task. The use of such a checklist would also avoid misinterpretation of the data provided by the customer. A standard requirements list is a recognized way to overcome such issues in a design environment [Pahl and Beitz]. This would also help in developing databases of inputs for future reference. A formal document like the requirements list also helps in developing a sense of responsibility on the part of the frame designer while interpreting the customer inputs and deriving a detailed requirements list. The requirements list could also be circulated to other departments of WMP which would ensure the capture of any misinterpreted data by the designer who is generating the requirements list. This would also serve as an important document in training any new frame designer that WMP would employ.

Conceptual design

When designing a new frame, the designer selects a similar baseline design that represents past success. This is a good way to start in the absence of a goodness measure for a design based on sound engineering principles. The risk with such a system is that there is no way of knowing how optimal the earlier design was. The crate might have been over designed and hence worked fine in earlier cases. There may be more efficient configurations of the crate, which may serve the purpose with far less material cost and reduced weight. In the absence of a baseline the frame configuration is entirely decided based on the experience of the frame designer along with design specification. In such cases the number of members and their orientations are not based on sound engineering principles but purely on experience. Such configuration may not necessarily yield low deflection or stresses in the frame. This leads to a purely trial and error method of design and one that cannot be proven until a prototype is built and tested.

The other important step in designing a frame is choosing the member cross-sections for the initial prototype. WMP stocks different cross-sectional sizes of round, rectangular, or square tubes of various gauges. The decision of what material and cross-section is to be used is based solely on the fabricator's experience. At the preliminary stage a cost/strength/cross-section matrix on each of the materials used for crate construction could assist the designer in making an informed decision based on engineering principles rather than experience.

An engineering tool used to calculate stress and deflection for a given frame configuration with all its cross-sections defined would be beneficial at this stage. The tool would enable the designers to explore different tube sizes for a given frame configuration in a matter of few hours and would give outputs like stresses and deflections in each member of the frame. This would be an input to an evaluation matrix comprising different options the designer has explored and factors like stress, deflection, cost, weight as criteria. A similar process could be followed by the frame designer in arriving at a suitable frame configuration to transport the vehicle. With such a tool, the designer and the management can make an informed decision on the type of frame they would like to build even before prototyping and testing.

Prototyping and testing

After arriving at a particular frame configuration based on the frame designer's experience, 3 to 5 prototypes are built. As discussed in Chapter 2, these prototypes have almost the same frame configurations except for small variations in some design features included to address some special customer requirements or design specifications, like locking mechanisms. Therefore the 5 prototypes are not structurally different from one another. The engineering tool discussed above would help the frame designer break away from conventional thinking and explore different frame configurations which have different load carrying paths.

The prototypes built are then subjected to a couple of crude tests. In the first, the crate along with the vehicle is fork lifted to a certain height. The frame is then visually inspected and maximum deflection is measured. A limit of ¾ inch is set on the maximum deflection. If the maximum deflection in the frame that is being tested is below the limit value and there is no failure observed in any of the members, the frame is assumed to be safe. The other test is for stability in which the vehicle is loaded onto the frame and fork lifted and driven around. Again it is visually inspected for stability problems like the bouncing of the vehicle, whether the locking mechanisms are serving their design intent. This test is to ensure that the vehicle does not fall off or damage other components when being transported.

Furthermore, the tests and visual inspection of the fabricated crate do not reveal much as to the stresses and deflection in each member. If the design is not satisfactory, increasing the gauge thickness of the tube is the most common approach to rectifying the problem. Adding additional members no doubt increases the stiffness and reduces deflection, but may not be the best way to design frame structures. As a result, WMP may have a frame that works but is highly over designed, costly and bulky. Once the various design options are fabricated, management chooses a single design based on visual appearance and past experience. At this stage the results obtained from the computer aided engineering tool would be beneficial in cross verifying the test results and locating high stress points that may need redesigning.

The method of choosing a design based solely on visual inspection is not optimal. Valuable assets including time and money are lost in prototype construction. Incorporating the comparison of various design engineering data will aid in determining the best possible design. Further, since no cost analysis is done at this stage, it is not possible to gauge a design through comparison of costs associated with material and manufacturing. The computer aided engineering tool used to do strength calculation could also be used to generate a preliminary bill of materials. For each design analyzed it could output a table of the cross-sections used and their length. Preliminary cost estimation could be done at this stage and an approximate total cost could be calculated by incorporating different factors to account for manufacturing and assembly. Having the costs presented with each design will allow WMP to conduct a cost-benefit analysis by comparing different design features. The computer aided tool would allow the management to make a more informed decision on finalizing “The” crate for detailed design and mass production.

Detail design

After a frame design has been finalized, a 3D model of the frame is built using Solidworks™ package. Detail drawings with revision numbers detailing all components, weld locations, sub assemblies, dimensions, tolerances and nomenclature of components along with the bill of materials is created. The frame designers use the final prototype to build jigs and fixtures as illustrated in the section, finalizing the design in Chapter 2. The prototype frame is shipped to the customer. The frame is then subjected to a set of formal tests at customer location as described in Chapter 2. The use of a computer aided engineering tool to compute stresses and deflection would give WMP a higher level of confidence in their product when subjected to customer specific tests.

Failure modes and effect analysis

The FMEA chart shown in Table 2 to Table 4 illustrates how certain attributes from current practices that may lead to failure in design [Pahl and Bietz].

Table 2: Failure Modes and Effects Analysis of the current design process

System/ Component/Function	Incorrect customer inputs	Starting with an existing baseline
Potential Failure mode	Crate that does not meet customer specifications, under/over designed	Non-optimized solution, expensive design
Potential effects of failure	Redesign from scratch, Loss of time, money due to re-work, loss of order	Unexplored design space, over/under designed, rework
Severity	High	Medium

Cause of failure	No checklists	Lack of engineering knowledge based design, decisions based solely on experience
Occurrence	Medium	High
Detection	Medium	Low

If the customer inputs and requirements are captured incorrectly, the final frame design may not meet the customer's expectation. This would result in wasted company resources, time and reduced customer satisfaction. The solution for this problem is to use a requirements list. Starting with an existing baseline and modifying the baseline to suit current needs may result in an over designed or an under designed crate. The effects of the above mentioned failure mode is unexplored design space, rework, and higher product cost.

Table 3: Failure Modes and Effects Analysis of the current design process

System/ Component/Function	Material selection and sizing of structural members	Initial frame configuration
Potential Failure mode	Improper material/cross-section for preliminary designs	Arriving at an inefficient design
Potential effects of failure	Additional members to be added to counter low strength structure increased weight, cost, number of prototypes, trial and error	Increased number of prototypes, failure to exploit the complete design space, management unaware of the best solution, increased time and cost
Severity	High	High
Cause of failure	No available method for comparing solutions, experience based selection, not able to check stiffness before starting to build prototypes	Design solely based on experience, Trial and error method of arriving at a solution, No engineering analysis done to verify the design
Occurrence	High	High
Detection	Medium	Low

In the absence of an initial base line, the designer arrives at a frame configuration and tube sizing purely based on his experience. The potential failure mode associated with these tasks is arriving at an inefficient frame configuration in terms of load path, weight, cost and improper material/cross-section for preliminary designs. A solution for this failure mode is to use a computer aided engineering tool to analyze the frame configuration and have the necessary data like stresses deflection before finalizing the design and prototyping.

Table 4: Failure Modes and Effects Analysis of the current design process

System/ Component/Function	Designers
Potential Failure mode	Retirement/Quitting
Potential effects of failure	Experience is lost. The next designer may not know the thumb rules used by the previous designer, Increased time for designing a new frame, Costly mistakes
Severity	High
Cause of failure	Current system of design depends solely on the experience of a few designers, no data/documentation of the thumb rules exist, non-systematic design, no documented design rules
Occurrence	Medium
Detection	High

In an organization such as WMP which heavily depends on a few key experienced individuals to design and prototype their products the most severe failure mode is the frame designers themselves. If a frame designer retires or decides to quit WMP, the experience associated with the designer is lost to the company. The new designer may not know the thumb rules used by the previous designer and results in increased time for designing a new frame. The solution to this problem is in migrating from the current design process to a systematic approach. The systematic approach would emphasize proper documentation of each phase of the design cycle using formal templates, requirements list, proper evaluation criteria in the conceptual design phase. The use of a computer aided engineering tool would emphasize virtual prototyping and engineering analysis. This would help the designers make an informed decision on the framed configuration based on stresses and deflection before starting to build prototypes. This would also increase the design space and encourage innovative solutions while designing.

CHAPTER 4

DESIGN ENABLER TOOL

Frame analysis design enabler tool

It is true that most commercial CAD/CAE packages would be able to perform the tasks and recommendations described in Chapter 3, but the management would incur additional costs of having specialized personnel to operate the CAD/FEA package coupled with the licensing costs associated with the CAD/CAE package. Furthermore, most SMEs would not use many of the features that they would have to pay for in a commercial CAD/CAE package and would prefer to have a customized computer aided tool that would assist the designers at targeted stages of the design process specific to WMP.

The case study discussed in Chapters 2 and 3 forms the basis for building a computer aided “Design Enabler Tool” (henceforth referred to as the Tool) that would assist the designers at specific stages of the design process. This Tool is based on classical matrix structural analysis with limited load and restraint capability designed to simplify the analysis process for designers with limited knowledge of engineering fundamentals. The Tool incorporates the recommendations from the case study of the design process followed by WMP.

The Tool that was developed for WMP facilitates engineering analysis that was noticeably absent in SME’s current design process. The Tool shown in Figure 17 is specific to WMP. It consists of a pre-processing module, where the user inputs the structural parameters to define an initial frame configuration by providing joint coordinates, member connectivity, loads, and fixity conditions. Then the computer program computes a stiffness matrix, load vector and then solves a set of linear simultaneous equations for unknown displacements. The post-processing module then computes member end actions/forces, support reactions, stresses, and writes all of the above results into output text files. The graphics module then plots a 2D top view of the frame with a complete bill of material used in the frame. In this Chapter, the Tool is explained in detail, covering the analysis technique used to compute displacements in the entire structure under a system of loads and restraints.

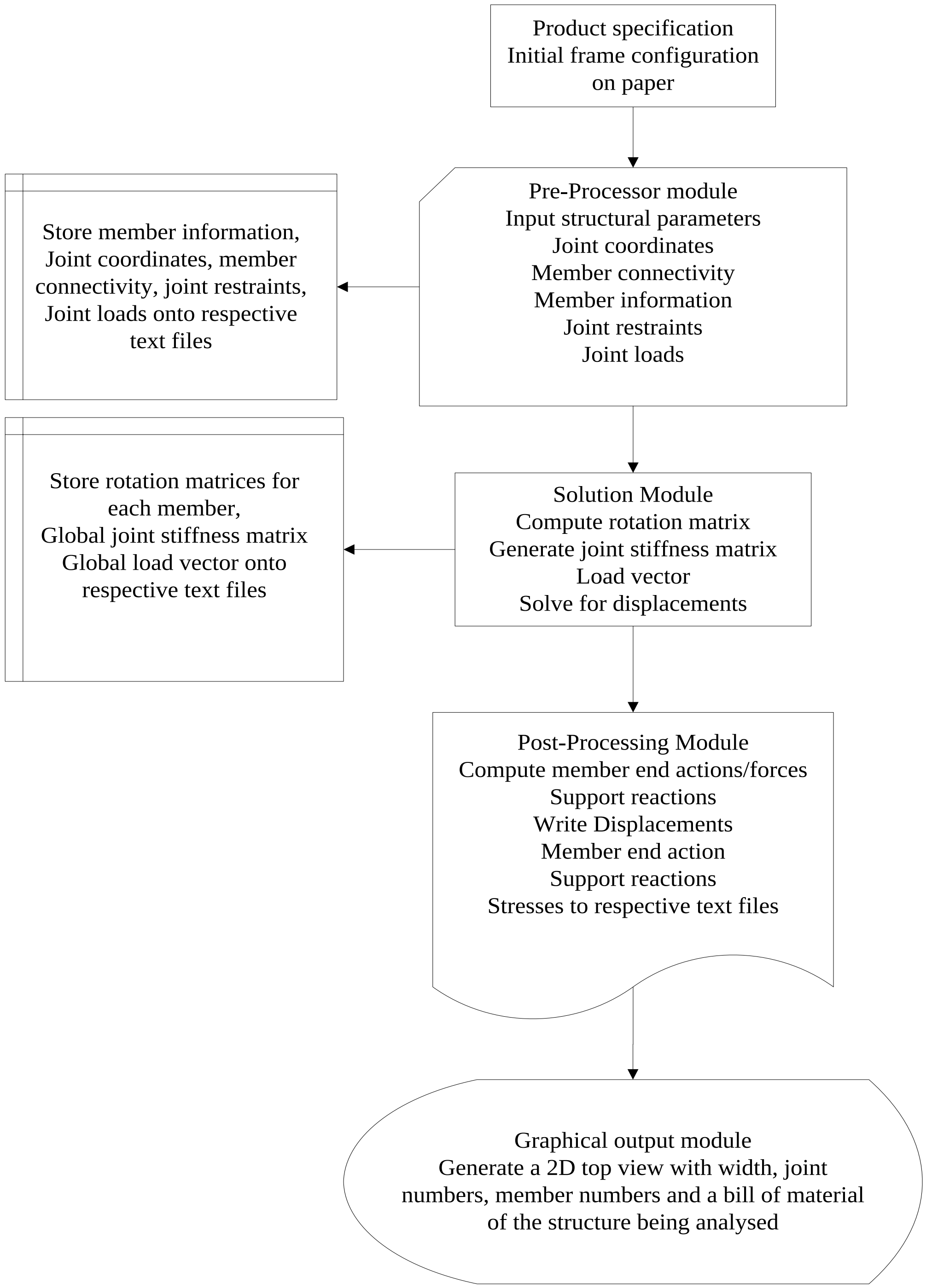


Figure 17: Design Enabler tool based on classical matrix structural analysis with limited load and restraint capability

This Chapter also covers the programming details in the form of detailed flowcharts. Flowcharts are illustrated for different stages or parts of the entire program that consists of a pre-processing module, a solution module and a post processing module as shown in Figure 17.

The Tool has been built to assist the frame designer, who is not an engineer, in designing frames using engineering principles rather than having to base the design purely on experience. The fabricator need not know the intricacies of engineering principles that the Tool employs, like the matrix method of frame analysis. The Tool's intention is not to completely automate the frame design process and eliminate the frame designer, but to equip the designer with some powerful engineering tools to compute stresses and deflection in the frame before prototyping and subjecting the frame to physical tests. The use of the Tool will save valuable time in terms of prototyping, testing and most importantly quantitatively assessing the design options. This would result in significant cost and time saving for WMP. Furthermore, the frame designer is able to think out of the box in arriving at different frame configurations by creating virtual prototypes and assess his ideas using the stress and deflection values without having to physically test his ideas.

From the case study it is observed that engineering analysis during conceptual stage, while evaluating different frame configuration, in embodiment design was notably absent in the current design process followed by WMP. Therefore, engineering analysis being an important task in quantitatively assessing different crate designs, an engineering analysis module was first developed and implemented. With the aid of the engineering analysis module, the designer is able to analyze a particular crate configuration in a matter of a few hours as compared to a few weeks in building and testing a crate prototype, making suitable changes to arrive at a concept design of a crate. This Tool enables the designer to quickly explore various design alternatives before starting to build a prototype. Furthermore, the management could use this module to generate concept drawings that would help in marketing and preliminary contract bidding.

The following sections in this Chapter discusses classification of frames, stiffness method of analyzing structures, derivation of structural stiffness matrix, global axis system and structural axis system, rotation of axis, transformation of member stiffness matrix to joint stiffness matrix using rotation of axis. All of the above computations are carried out by the Tool using the initial information provided by the user.

Types of framed structures

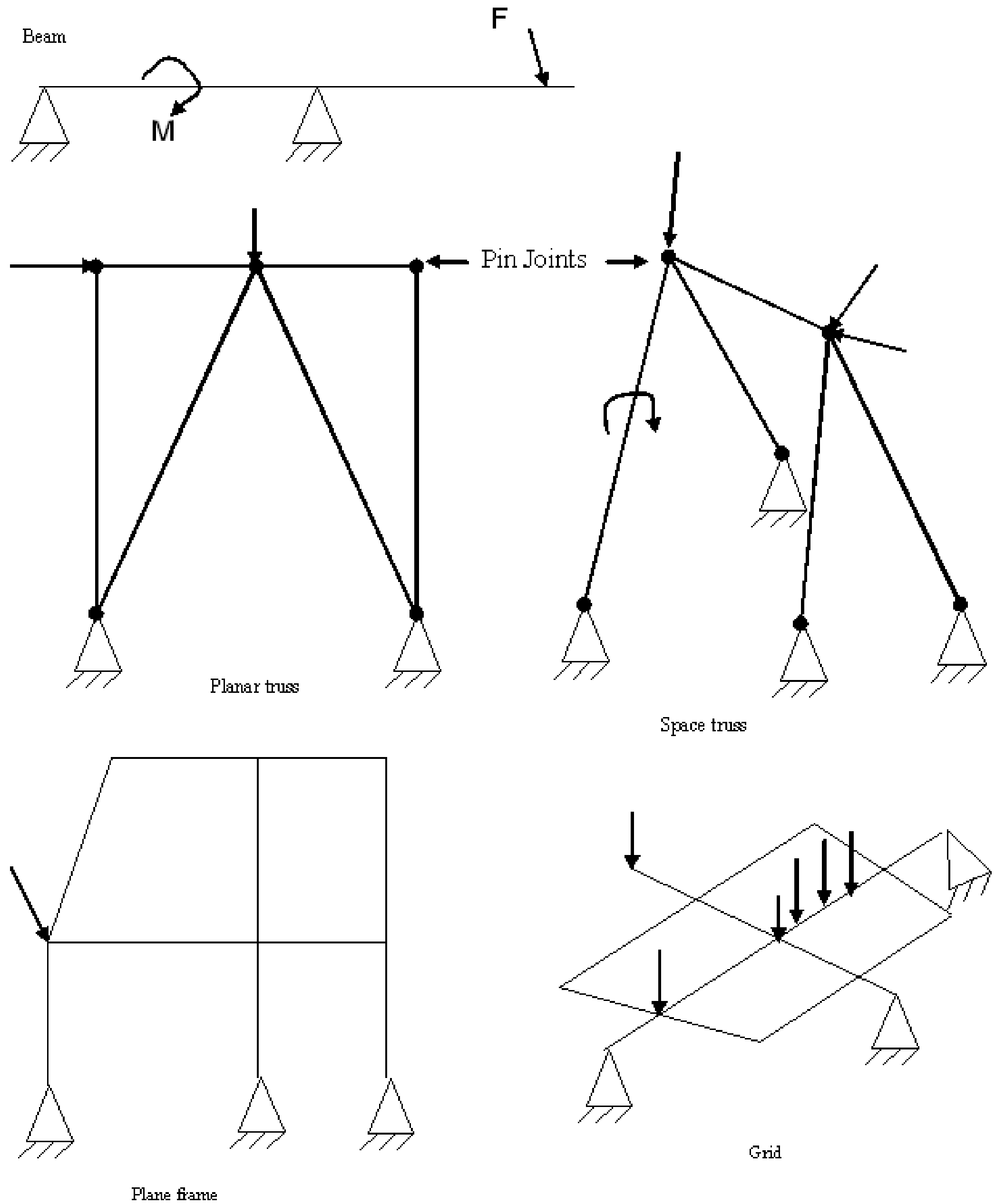


Figure 18: Types of framed structures: Beam, Planar truss, Space truss, Plane frame, Grid

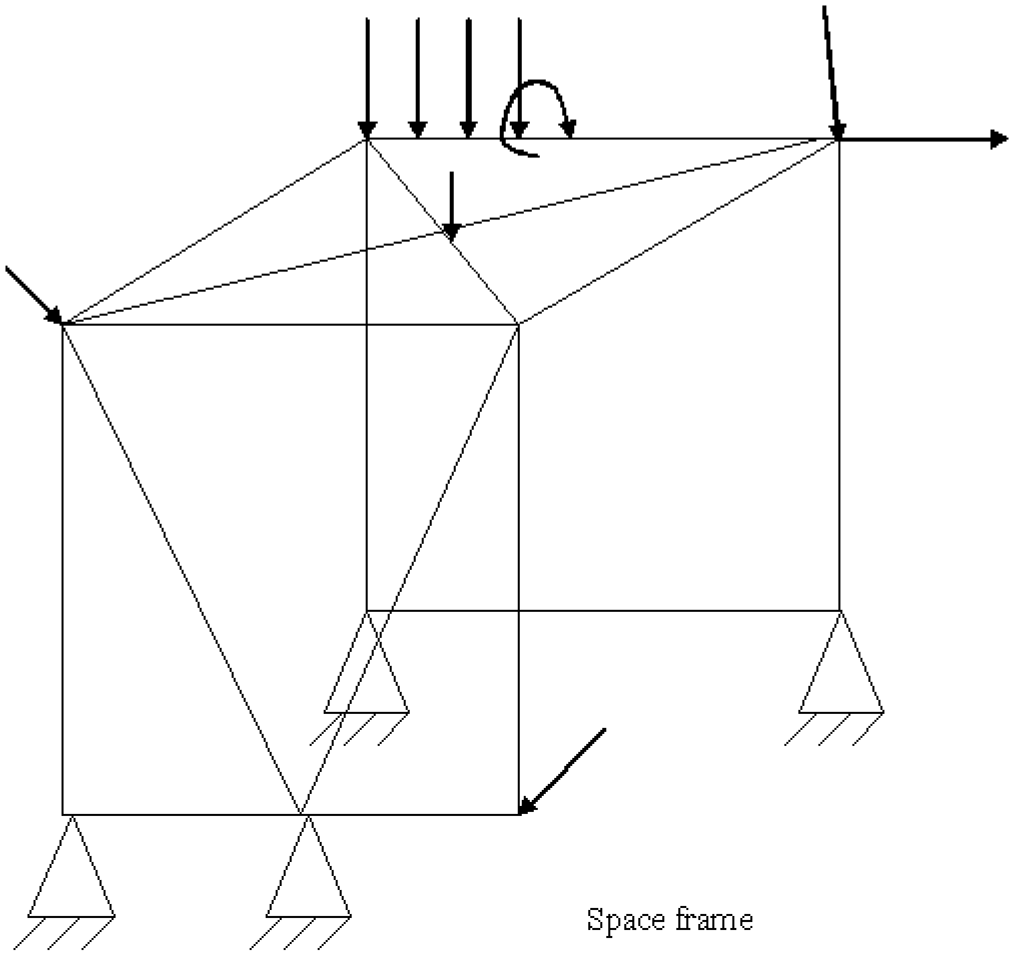


Figure 19: Types of framed structure: Space frame

All the structures that WMP manufactures can be classified as *framed structures*. The framed structures consist of members that have one dimension (Length) much greater than the other two dimensions (cross-section) and these members can be satisfactorily idealized using line elements [Balfour]. The joints (nodes) of a framed structure are defined to be the points of intersection of structural members, as well as free ends and points of support. The loads on these structures can be concentrated force, distributed load, and couples. Most textbooks on computer analysis of framed structures classify the framed structures into beams, plane trusses, space trusses, plane frames, grids, and space frames as illustrated in Figure 18 and Figure 19 [Balfour],[Weaver and Gere] and [Holzer].

Beams consist of straight or curved members that are supported at one or more locations. In the case of cross-section of the beam being symmetric about an axis, all the forces applied on the beam act in a plane containing the axis of symmetry. The moment vectors acting on the beam are normal to this plane and the beam deflects in the same plane without twisting about its axis. In the case of beams with unsymmetrical cross-section, the loading could result in twisting about an axis passing through the centroid of the cross-section.

A plane truss is a system of members lying in one plane and interconnected by hinged joints. All the applied forces are assumed to act in the plane of the structure. The analysis of a truss subjected only to joint loads will result in axial forces of tension and compression in members and joint translations result from axial strains in members. The number of possible displacement components at each node for a plane truss is two, translation in x and y directions of the plane.

Space truss are similar to plane trusses except that the members can be oriented in any direction in space. Also the forces acting on the joints could be in any arbitrary direction. Truss members develop only axial tension or compression forces. The nodes of a space truss have three possible displacement components, translation in x, y, and z directions respectively. For both plane trusses and space trusses, loads are assumed to be applied to joints only, thus neglecting self weight of members, only tension or compression axial forces are developed and no moment vectors are developed.

Plane frames are structures constructed of members lying in a single plane and the cross-sections having axis of symmetry in that plane. The joints between members may be hinged or rigidly connected. The forces acting on the frame are in-plane and the moment vectors are perpendicular to the plane of the structure. The nodes of a plane frame have three possible displacement components, translation in x and y direction and rotation about z direction which is perpendicular to the plane of the frame.

A grid is a plane frame structure with hinged or rigid connection and applied forces are normal to the plane of the structure. In a grid structure, all the moment vectors are in plane of the grid. This may result in torsion as well as bending in some of the members. The nodes of a grid have three possible displacement components, rotation about x and y direction (plane of the grid) and translation in z direction which is perpendicular to the plane of the grid.

Space frames are the most general type of frames structures. Space frames have no restrictions on the location of joints, connections at the joints, directions of members, or the directions of applied loads. The members of space frame can carry internal axial forces, torsion, bending moments and shearing forces in both principal directions of the cross-sections. Since space frames are the most general types of frame, the Tool is built to solve such structures. All other types of frames could be solved as a space frame with appropriate boundary conditions. Since the Tool can be used to analyze space frames with rigid connections and symmetric cross-sections, WMP could use this program to analyze any kind of rigidly joined frame, with no restrictions on the orientation of frame members, however, to simplify the input and interpretation of results for the designer with limited understanding of different load types and displacement degree of freedom restraints, the computer program has restrictions on the type of loads applied on the structure and the restraint conditions. If in the future, WMP decides to employ an engineer to design the frames, the engineer could uncomment parts of the code to incorporate asymmetric cross-sections and remove restrictions on loading and restraint conditions.

Stiffness method of analyzing space frames

This section describes the implementation of classical stiffness method of analyzing space frames. This method of solving framed structures are discussed in numerous finite element textbooks and this work follows the procedure outlined in the book “Matrix Analysis of Framed Structures” by Weaver and Gere. If a structure is in a state of stable equilibrium and small displacement theory is valid, then there exists a unique relationship between the deformation of structure and the applied load system. The frames built by WMP can be analyzed as static structures. The two main conditions for which a frame is analyzed are as follows; (1) The frame placed on ground and loaded with a vehicle, (2) The frame along with the vehicle fork lifted. Both of these load cases can be approximated as static analysis and the whole system will be in equilibrium. The structure is assumed to be linearly elastic; there is a linear relationship between the stresses and strains in the material and the applied loads and resulting displacements. The frames also should not yield during operation. The frame should obey Hooke’s law and should regain its original geometry when unloaded. If the frame yields, the Tool is no longer valid to predict the displacements and member forces.

The components of force and displacement at a node or joint are stored in a one dimensional array called the nodal force vector and displacement vector. There are six nodal degrees of freedom for a space frame node/joint are six and the nodal force and displacement vectors are as shown below.

$$\text{Nodal force vector} = \begin{bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{bmatrix} \qquad \text{Nodal displacement vector} = \begin{bmatrix} u_x \\ u_y \\ u_z \\ \theta_x \\ \theta_y \\ \theta_z \end{bmatrix}$$

Where,

F is set of linear force components.

M is set of moments components.

u is set of linear displacements components.

θ is set of rotational displacements components.

The relationship between the applied loads and resulting displacements for a node of the space frame members takes the following form.

$$\begin{bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} K_{11} & K_{12} & K_{13} & K_{14} & K_{15} & K_{16} \\ K_{21} & K_{22} & K_{23} & K_{24} & K_{25} & K_{26} \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ K_{61} & K_{62} & . & . & . & K_{66} \end{bmatrix} \begin{bmatrix} u_x \\ u_y \\ u_z \\ \theta_x \\ \theta_y \\ \theta_z \end{bmatrix} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(4.1)}$$

$\{F\} = [K]\{\Delta\}$, Where F is the nodal force vector, K is the structural stiffness matrix and Δ is the nodal displacement vector.

The analysis of structures using the stiffness equation $F = K\Delta$ has three primary steps [Belfour].

1) Assemble the stiffness matrix where the elements of the stiffness matrix are the coefficients of a set of simultaneous equations. The stiffness matrix is a property of the structure and is independent of loading on the structure.

2) Generate loading vector *F*.

3) Solve the simultaneous equations that yield the unknown displacements Δ caused by the applied loading *F*.

The above steps form the general approach to the solution of frames using stiffness method. The Tool implements classical matrix frame analysis to compute displacements for the space frame structure with simplified load and displacement restraint conditions catering to the designers with limited understanding of details of engineering analysis.

Structural stiffness matrix

Consider a linearly elastic body acted upon by a system of forces ***F***, which causes displacements Δ in the direction of applied forces as shown in Figure 20.

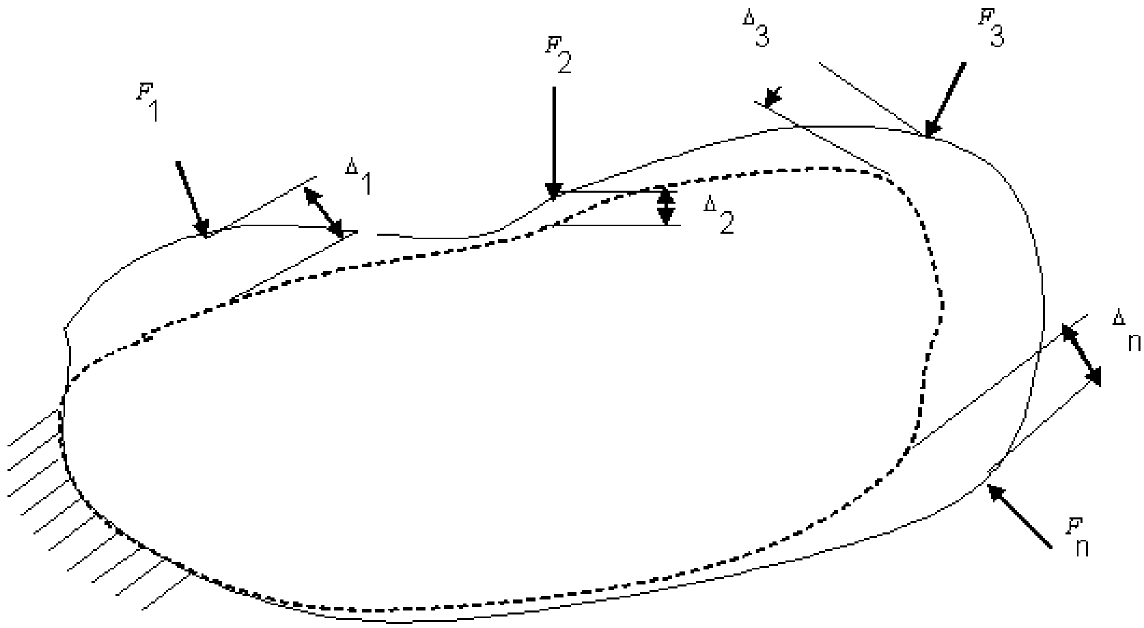


Figure 20: Deformation of an elastic body[Belfour]

The total work done during the application of the forces is

$$W = \frac{1}{2}(F_1\Delta_1 + F_2\Delta_2 + F_3\Delta_3 + ... + F_n\Delta_n) \text{ ………………. (4.2) [Belfour]}$$

In an elastic body, the work done by external load is equal to the strain energy ***U*** gained by the body.

$W = U$ ………………. (4.3) [Belfour]

The change in strain energy of the body due to an infinitesimal variation of one displacement, say Δ_1 while all other displacements are held constant is

$$dU = \frac{\partial U}{\partial \Delta_1} d\Delta_1 \text{ ………………. (4.4) [Belfour]}$$

And the change in load F_1 is

$$dF_1 = \frac{\partial F_1}{\partial \Delta_1} d\Delta_1 \ldots\ldots\ldots\ldots\ldots\ldots \text{(4.5) [Belfour]}$$

Neglecting the higher order terms, the change in work done is

$$dW = F_1 d\Delta_1 \ldots\ldots\ldots\ldots\ldots\ldots \text{(4.6) [Belfour]}$$

Change in work done is equal to change in strain energy

$$dW = dU \ldots\ldots\ldots\ldots\ldots\ldots \text{(4.7) [Belfour]}$$

Substituting equation 4.4 and 4.6 in 4.7, we have

$$F_1 d\Delta_1 = \frac{\partial U}{\partial \Delta_1} d\Delta_1 \ldots\ldots\ldots\ldots\ldots\ldots \text{(4.8) [Belfour]}$$

Differentiation of equation 4.8 with respect to displacement that is varied yields

$$\frac{dW}{d\Delta_1} = F_1 = \frac{1}{2}\left(F_1 + \frac{\partial F_1}{\partial \Delta_1}\Delta_1 + \frac{\partial F_2}{\partial \Delta_1}\Delta_2 + \frac{\partial F_3}{\partial \Delta_1}\Delta_3 + \ldots. + \frac{\partial F_n}{\partial \Delta_1}\Delta_n\right) \text{[Belfour]}$$

Therefore,

$$F_1 = \frac{\partial F_1}{\partial \Delta_1}\Delta_1 + \frac{\partial F_2}{\partial \Delta_1}\Delta_2 + \frac{\partial F_3}{\partial \Delta_1}\Delta_3 + \ldots. + \frac{\partial F_n}{\partial \Delta_1}\Delta_n \text{ [Belfour]}$$

Similarly, varying all other displacements one at a time, one obtains

$$F_2 = \frac{\partial F_1}{\partial \Delta_2}\Delta_1 + \frac{\partial F_2}{\partial \Delta_2}\Delta_2 + \frac{\partial F_3}{\partial \Delta_2}\Delta_3 + \ldots. + \frac{\partial F_n}{\partial \Delta_2}\Delta_n$$

.

[Belfour]

.

$$F_n = \frac{\partial F_1}{\partial \Delta_n}\Delta_1 + \frac{\partial F_2}{\partial \Delta_n}\Delta_2 + \frac{\partial F_3}{\partial \Delta_n}\Delta_3 + \ldots. + \frac{\partial F_n}{\partial \Delta_n}\Delta_n$$

Writing the above simultaneous equations in matrix form, the following is found

$$\begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ . \\ . \\ . \\ . \\ F_n \end{bmatrix} = \begin{bmatrix} \frac{\partial F_1}{\partial \Delta_1} & \frac{\partial F_2}{\partial \Delta_1} & \frac{\partial F_3}{\partial \Delta_1} & . & . & . & . & \frac{\partial F_n}{\partial \Delta_1} \\ \frac{\partial F_1}{\partial \Delta_2} & \frac{\partial F_2}{\partial \Delta_2} & \frac{\partial F_3}{\partial \Delta_2} & . & . & . & . & \frac{\partial F_n}{\partial \Delta_2} \\ . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . \\ \frac{\partial F_1}{\partial \Delta_n} & \frac{\partial F_2}{\partial \Delta_n} & \frac{\partial F_3}{\partial \Delta_n} & . & . & . & . & \frac{\partial F_n}{\partial \Delta_n} \end{bmatrix} \begin{bmatrix} \Delta_1 \\ \Delta_2 \\ \Delta_3 \\ . \\ . \\ . \\ . \\ \Delta_n \end{bmatrix} \quad \text{..................} \; (4.9) \; [\text{Belfour}]$$

The above equation 4.9 is the stiffness equation [Belfour]

$$F = K\Delta$$

The coefficients of the stiffness matrix are the derivatives that represent the rate of change of force with displacement. The generalized form of the coefficient of the stiffness matrix can be written as $\frac{\partial F_i}{\partial \Delta_j}$, that is the rate of change of force at location "i" of the structure with variation of displacement at location "j" of the structure and displacements at all other locations of the structure being held constant or zero[Belfour].

The complete stiffness matrix can be generated by applying unit displacement at each free node, one at a time and calculating the force system required to maintain equilibrium of the structure. Consider a space frame member with two nodes and six degrees of freedom at each node. If unit displacements and unit rotations are induced one at a time at each end of the member, the resulting restraint actions to maintain equilibrium of the member will constitute the elements of the member stiffness matrix .[Weaver,Gere]..

A space frame may consist of many members of different cross-sections and orientation connected together. To obtain a stiffness matrix for the entire structure using the above mentioned method is difficult and not possible to implement as a computer program. To counter this problem, the stiffness matrix is derived for a generalized space frame member in its member axis system. Figure 21 shows such a generalized space frame member.

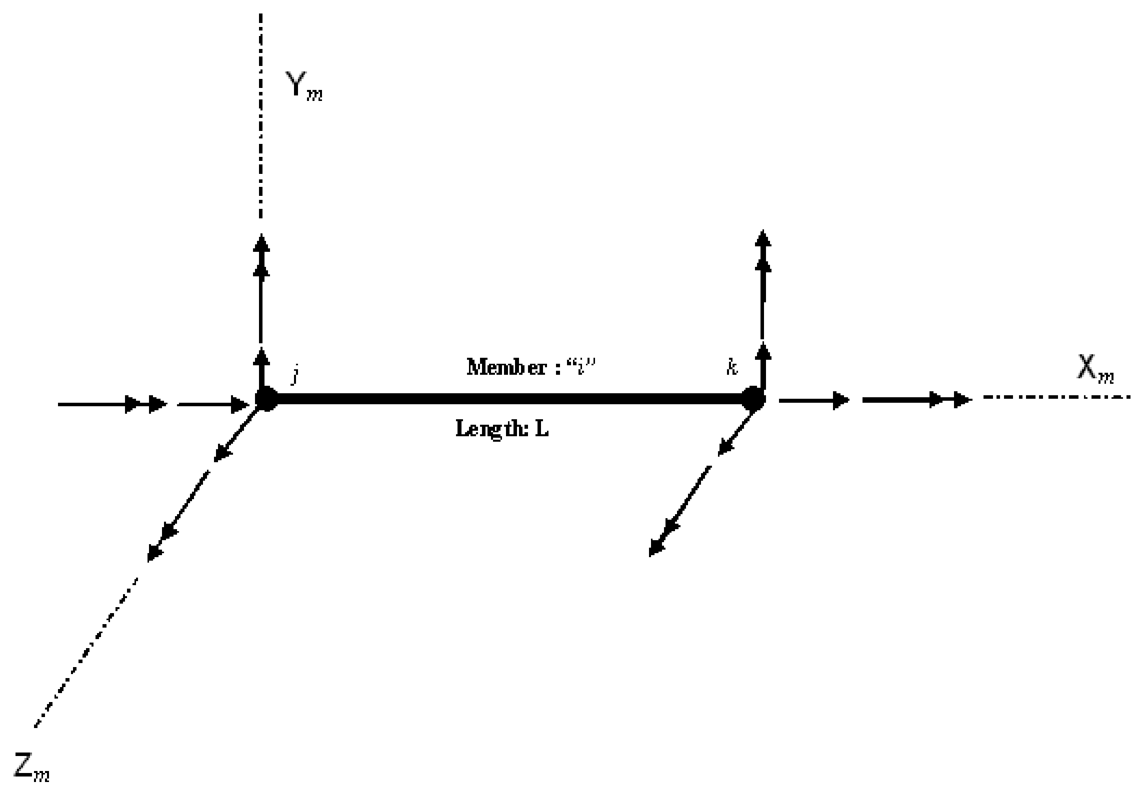


Figure 21: A generalized space frame member [Weaver,Gere].

Consider a prismatic space frame member "*i*" as shown in Figure 21. The single head arrows represent translational degrees of freedom and double head arrows represent rotational degrees of freedom. The end nodes of the member are denoted as "*j*" and "*k*". X_m, Y_m, Z_m are member oriented axis. X_m axis coincides with the centroidal axis of the member with positive sense from j to k. $X_m - Y_m$ and $X_m - Z_m$ planes are the principal planes of bending for the member.

The properties of the member shown in Figure 21 are as follows.

a) L = Length of the member.

b) A_x = Cross-sectional area of the member.

c) I_{xx} = Torsion constant, also known as J in strength of materials.

d) I_{yy} = Principal moment of inertia of the cross-section about Y_m axis.

e) I_{zz} = Principal moment of inertia of the cross-section about Z_m axis.

f) E = Modulus of elasticity.

g) G = Shear modulus.

The member stiffness coefficients for six possible types of end displacements are pictorially represented in Figure 22 and Figure 23 showing the force required to maintain equilibrium when unit displacements is applied at end “j” of the member.

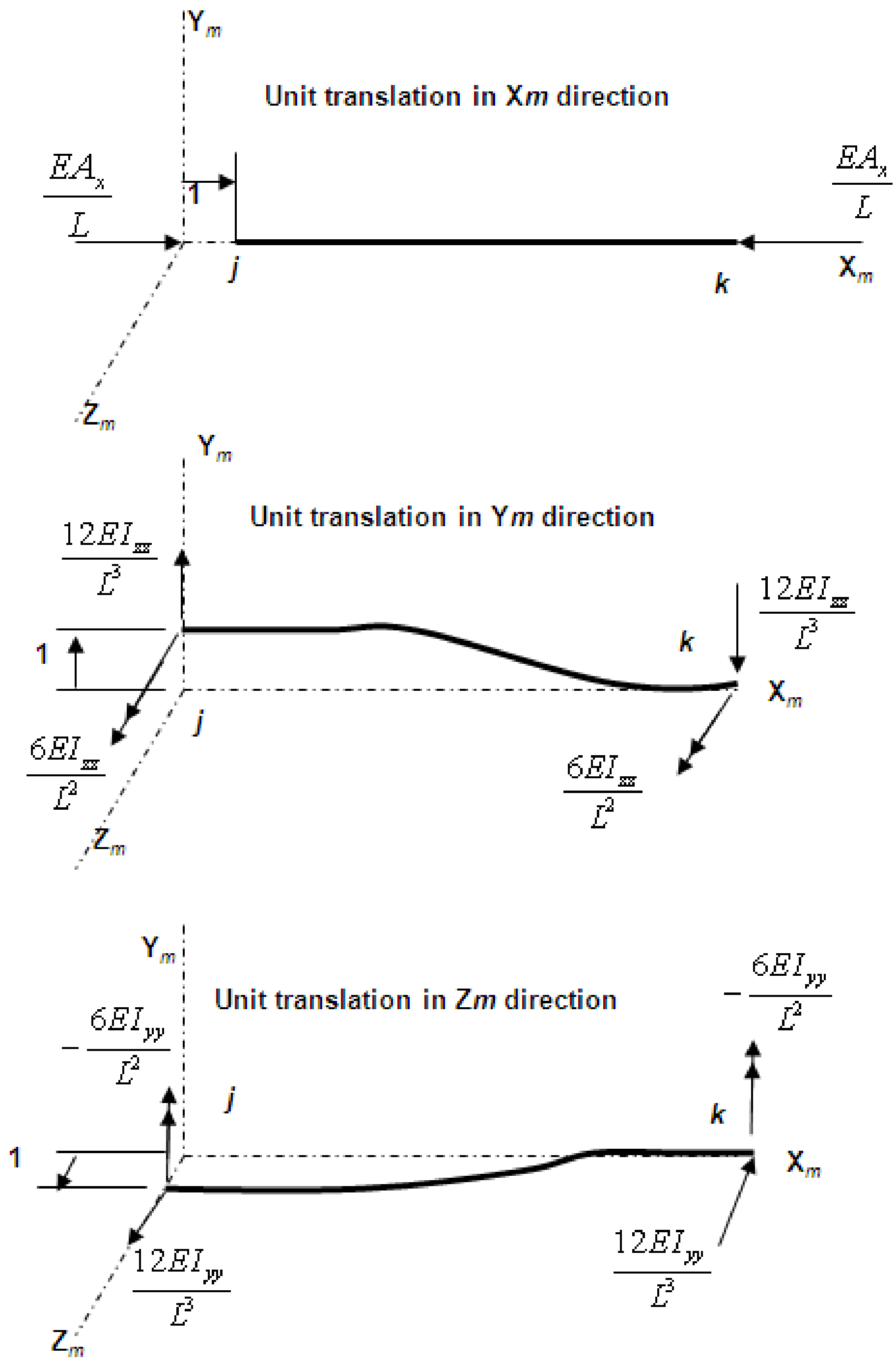


Figure 22: Unit values of displacements applied at end "*j*" and the corresponding stiffness values for each node .[Weaver,Gere].

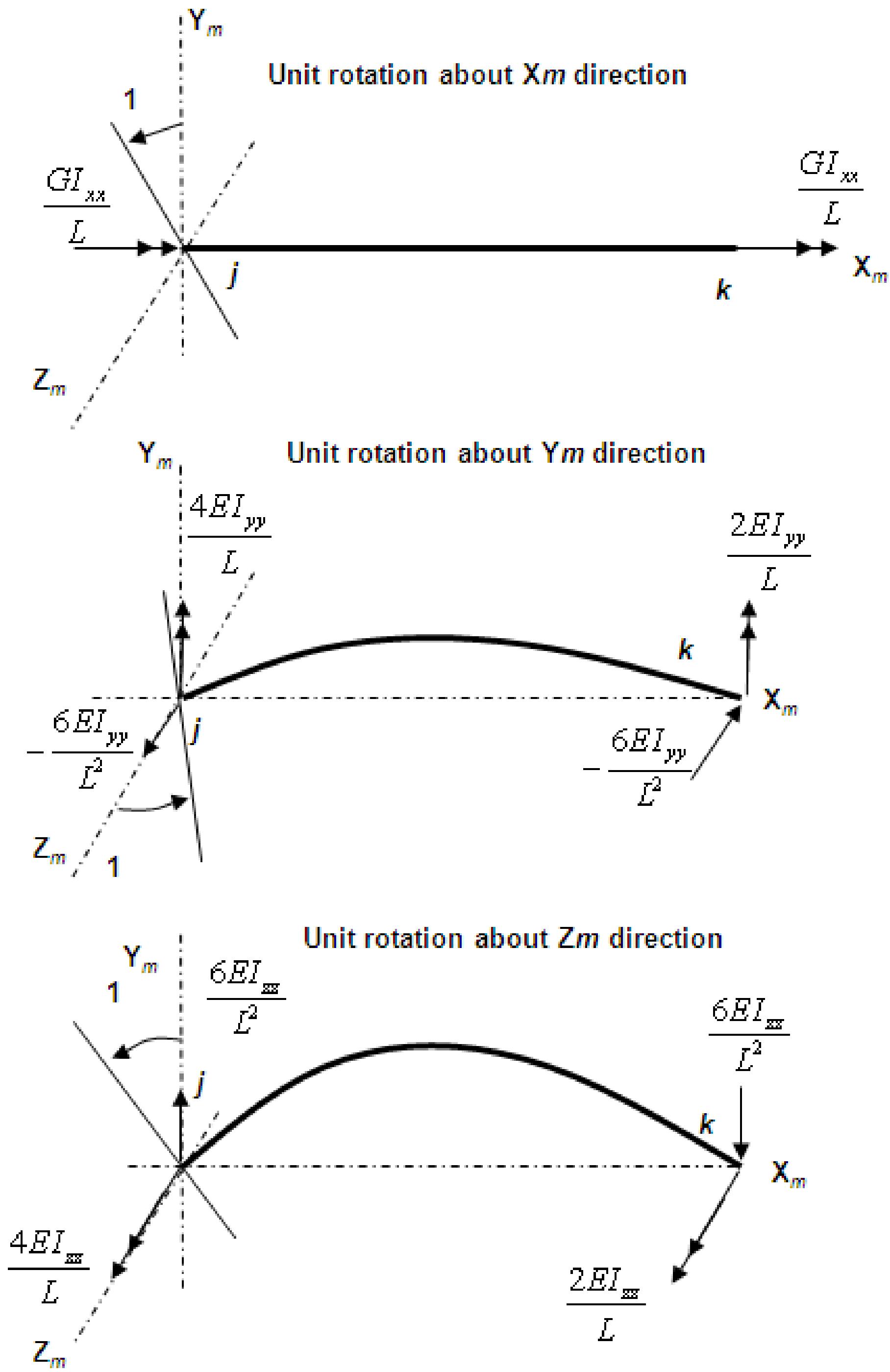


Figure 23: Unit values of rotations applied at end "*j*" and the corresponding stiffness values for each node [Weaver,Gere].

Similarly, six forces are obtained by applying unit displacements at end “k”. Table 5 shows the member stiffness matrix for a space frame member in member axis system.

Table 5: Member stiffness matrix for a space frame member in member axis system.

[Weaver,Gere]

$$S_{M_i} = \begin{bmatrix} \frac{EA_x}{L} & 0 & 0 & 0 & 0 & 0 & -\frac{EA_x}{L} & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{12EI_{zz}}{L^3} & 0 & 0 & 0 & \frac{6EI_{zz}}{L^2} & 0 & -\frac{12EI_{zz}}{L^3} & 0 & 0 & 0 & \frac{6EI_{zz}}{L^2} \\ 0 & 0 & \frac{12EI_{yy}}{L^3} & 0 & -\frac{6EI_{yy}}{L^2} & 0 & 0 & 0 & -\frac{12EI_{yy}}{L^3} & 0 & -\frac{6EI_{yy}}{L^2} & 0 \\ 0 & 0 & 0 & \frac{GI_{xx}}{L} & 0 & 0 & 0 & 0 & 0 & -\frac{GI_{xx}}{L} & 0 & 0 \\ 0 & 0 & -\frac{6EI_{yy}}{L^2} & 0 & \frac{4EI_{yy}}{L} & 0 & 0 & 0 & \frac{6EI_{yy}}{L^2} & 0 & \frac{2EI_{yy}}{L} & 0 \\ 0 & \frac{6EI_{zz}}{L^2} & 0 & 0 & 0 & \frac{4EI_{zz}}{L} & 0 & \frac{6EI_{zz}}{L^2} & 0 & 0 & 0 & \frac{2EI}{L} \\ -\frac{EA_x}{L} & 0 & 0 & 0 & 0 & 0 & \frac{EA_x}{L} & 0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{12EI_{zz}}{L^3} & 0 & 0 & 0 & -\frac{6EI_{zz}}{L^2} & 0 & \frac{12EI_{zz}}{L^3} & 0 & 0 & 0 & -\frac{6EI_{zz}}{L^2} \\ 0 & 0 & -\frac{12EI_{yy}}{L^3} & 0 & \frac{6EI_{yy}}{L^2} & 0 & 0 & 0 & \frac{12EI_{yy}}{L^3} & 0 & \frac{6EI_{yy}}{L^2} & 0 \\ 0 & 0 & 0 & -\frac{GI_{xx}}{L} & 0 & 0 & 0 & 0 & 0 & \frac{GI_x}{L} & 0 & 0 \\ 0 & 0 & -\frac{6EI_{yy}}{L^2} & 0 & \frac{2EI_{yy}}{L} & 0 & 0 & 0 & \frac{6EI_{yy}}{L^2} & 0 & \frac{4EI_{yy}}{L} & 0 \\ 0 & \frac{6EI_{zz}}{L^2} & 0 & 0 & 0 & \frac{2EI_{zz}}{L} & 0 & -\frac{6EI_{zz}}{L^2} & 0 & 0 & 0 & \frac{4EI_{zz}}{L} \end{bmatrix}$$

Rotation of axis

In order to solve the structure for displacements, a global joint stiffness matrix needs to be constructed in the global axis system. The reason being the displacements of the entire structure needs to be computed in one axis system that is common to the entire structure. The forces and displacements boundary conditions are also input in the global axis system. This is done to maintain uniformity throughout the structure. The member axis system can be different for every member in the structure. The applied loads are assembled into a global load vector, the computed displacements and the global joint stiffness matrix are in the global axis system. The global joint stiffness matrix is obtained by assembling the individual member stiffness matrix. The joint stiffness matrix being in global and member stiffness matrices being in member axis system, there is an obvious mismatch of co-ordinate system. Therefore, before assembly of the joint stiffness matrix, the member stiffness matrices for each member need to be transformed (rotation or translation). Only when all the elements of the member stiffness matrix are in the global axis system can they be assembled into the global joint stiffness matrix.

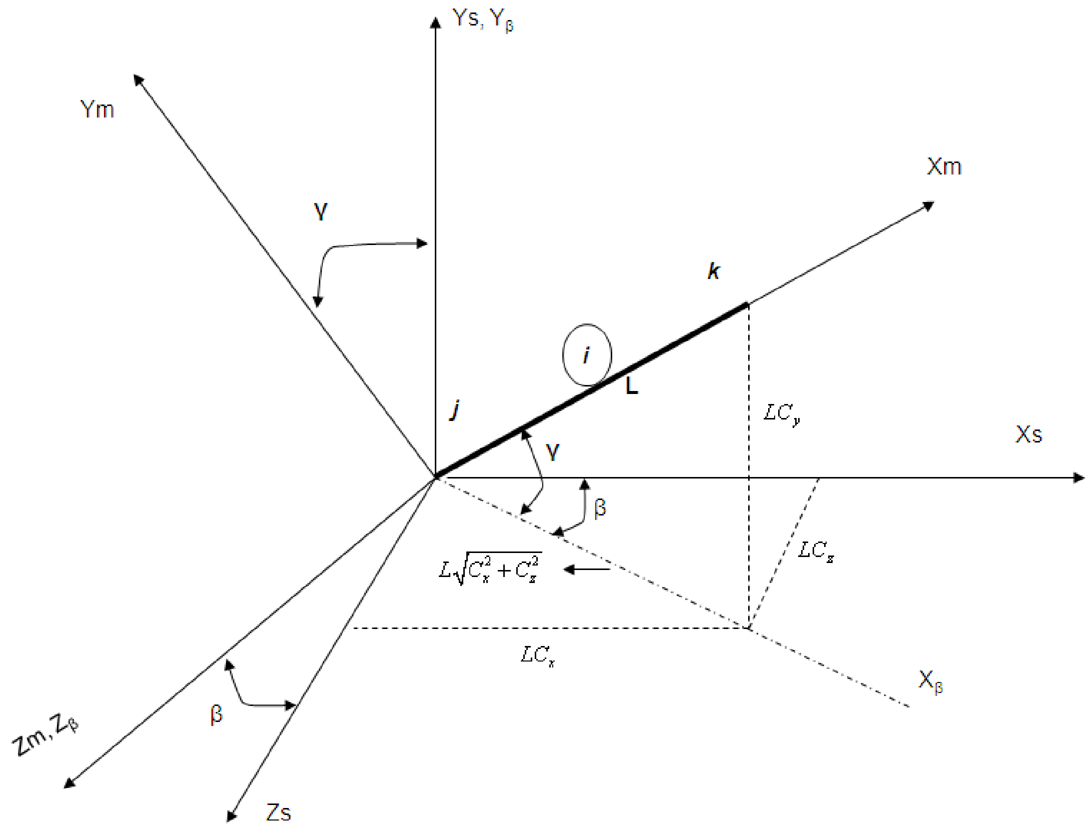


Figure 24: Rotation of axis in 3 dimensions for a space frame member [Weaver,Gere].

Consider a typical space frame member as shown in Figure 24. The x_S, y_S, z_S axis are parallel to the global coordinate system or the structural axis system. The x_M axis is the axis of the member, while possible directions of the y_M and z_M axis are many. One way to orient the system is to make the z_M axis lie on the $x_S - z_S$ plane. Axis transformation can be achieved by successive rotations of the axis to obtain the desired transformation from structural axis to the member axis. This can be done in two steps; the first is rotate by an angle β about the y_S axis. This results in a new intermediate axis system $x_\beta, y_\beta, z_\beta$. The rotation places the z_M axis in its final position at an angle β with the z_S axis as shown in above Figure 24. The second step in the transformation consists of rotation through an angle γ about the z_M axis. This rotation places, x_M and y_M axis in their final positions, as shown in Figure 24 [Weaver,Gere]..

The direction cosines for the member in terms of its coordinates of end points are as follows:

$$C_x = \frac{x_k - x_j}{L} \quad C_y = \frac{y_k - y_j}{L} \quad C_z = \frac{z_k - z_j}{L}$$

The length L of the member can be computed by the following expression

$$L = \sqrt{(x_k - x_j)^2 + (y_k - y_j)^2 + (z_k - z_j)^2}$$

The rotation matrix **R** that is used for transformation from member axis to structural axis can be developed following the two steps described above. The 3x3 rotation matrix $\mathbf{R_\beta}$ for the first rotation about the y_S axis through an angle β consists of direction cosines of β-axis with respect to the global or structural axis .[Weaver,Gere]..

$$\mathbf{R_\beta} = \begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix}$$

The functions $\cos\beta$ and $\sin\beta$ can expressed in terms of direction cosines of member "*i*" as shown in Figure 14. The rotation matrix $\mathbf{R_\beta}$ in terms of direction cosines becomes,

$$\mathbf{R_\beta} = \begin{bmatrix} \frac{C_X}{C_{XZ}} & 0 & \frac{C_Z}{C_{XZ}} \\ 0 & 1 & 0 \\ \frac{-C_Z}{C_{XZ}} & 0 & \frac{C_X}{C_{XZ}} \end{bmatrix} \text{ where } C_{XZ} = \sqrt{C_X^2 + C_Z^2}$$

The second rotation about the z_M axis through the angle γ can be handled similar to rotation through the angle β. In this step a rotation matrix $\mathbf{R}_\gamma$ contains the direction cosines of the member axis with respect to the β-axis and is given by,

$$\mathbf{R}_\gamma = \begin{bmatrix} \cos\gamma & \sin\gamma & 0 \\ -\sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Expressing the above rotation matrix in terms of the direction cosines of the member we have,

$$\mathbf{R}_\gamma = \begin{bmatrix} C_{XZ} & C_Y & 0 \\ -C_Y & C_{XZ} & 0 \\ 0 & 0 & 1 \end{bmatrix} \text{ where } C_{XZ} = \sqrt{C_X^2 + C_Z^2}$$

The single transformation matrix **R** from the structural axis to the member axis is the product of $\mathbf{R}_\gamma$ and $\mathbf{R}_\beta$.[Weaver,Gere]

$\mathbf{R} = \mathbf{R}_\gamma \, \mathbf{R}_\beta$

$$\mathbf{R} = \begin{bmatrix} C_X & C_Y & C_Z \\ \dfrac{-C_X C_Y}{C_{XZ}} & C_{XZ} & \dfrac{-C_Y C_Z}{C_{XZ}} \\ \dfrac{-C_Z}{C_{XZ}} & 0 & \dfrac{C_X}{C_{XZ}} \end{bmatrix} \text{………………. (4.10) [Weaver,Gere].}$$

The rotational transformation matrix for a space frame will take the below form, with the size of the matrix being 12 x 12. It can also be shown that for a rotation matrix, its inverse and transpose are the same.[Weaver,Gere]

$$\mathbf{R_T} = \begin{bmatrix} R & 0 & 0 & 0 \\ 0 & R & 0 & 0 \\ 0 & 0 & R & 0 \\ 0 & 0 & 0 & R \end{bmatrix}$$

Also, $\mathbf{R^T = R^{-1}}$………………. (4.11)

Conversion of member stiffness matrix from member axis to structural axis

The force-displacement relationship in the member axis system for a space frame member "*i*" may be expressed as follows.

$$\begin{bmatrix} F_{M_j} \\ F_{M_k} \end{bmatrix} = \begin{bmatrix} S_{M_{jj}} & S_{M_{jk}} \\ S_{M_{kj}} & S_{M_{kk}} \end{bmatrix} \begin{bmatrix} D_{M_j} \\ D_{M_k} \end{bmatrix}$$ ………………. (4.12) [Weaver,Gere].

Subscripts "*j*" and "*k*" represent the two nodes associated with member "*i*". The terms F_{M_j}, F_{M_k} are nodal force vectors of size 6 x 1 in the member axis system and D_{M_j}, D_{M_k} are nodal displacement vectors of size 6x1 in the member axis system. The stiffness matrix is 12x12 as shown in Table 3.

The above equation 4.12 can be expressed with respect to the structural axis system by using the rotation matrices derived in the preceding section. Applying rotation matrices for transforming the nodal force vector and displacement vector, we get

$$F_M = R * F_S$$
$$D_M = R * D_S$$ ………………. (4.13) [Weaver,Gere].

F_S and D_S are nodal force vector and displacement vector in the structural axis system.

Substituting equation 4.13 into 4.12 we obtain the following.

$$\begin{bmatrix} R & 0 \\ 0 & R \end{bmatrix}\begin{bmatrix} F_{S_j} \\ F_{S_k} \end{bmatrix} = \begin{bmatrix} S_{M_{jj}} & S_{M_{jk}} \\ S_{M_{kj}} & S_{M_{kk}} \end{bmatrix}\begin{bmatrix} R & 0 \\ 0 & R \end{bmatrix}\begin{bmatrix} D_{S_j} \\ D_{S_k} \end{bmatrix}$$

The above equation can be concisely expressed as

$R_T F_S = S_M R_T D_S$ ………………. (4.14) [Weaver,Gere].

$F_S = R_T^{-1} S_M R_T D_S$ ………………. (4.15) [Weaver,Gere].

Since, $\mathbf{R^T = R^{-1}}$

Equation 4.15 becomes

$$\begin{aligned} F_S &= R_T^T S_M R_T D_S \\ F_S &= S_{MS} D_S \end{aligned}$$ ………………. (4.16) [Weaver,Gere].

S_{MS} is the member stiffness matrix for structural axis.

$S_{MS} = R_T^T S_M R_T$ ………………. (4.17) [Weaver,Gere].

The above sections discussed classification of frames, the stiffness method of analyzing structures, derivation of structural stiffness matrix, member axis system and structural axis system, rotation of axis, transformation of member stiffness matrix to a joint stiffness matrix using rotation of axis. The sections below describe the computer implementation of the stiffness method of analyzing frames, the required inputs that the user has to provide, the computations performed by the computer program, the outputs of the computer program.

Computer program for analysis of space frame structures

The computer program has a pre-processing module, where the user inputs the structural parameters to define an initial frame configuration by providing joint coordinates, member connectivity, loads, and fixity conditions . Then the computer program computes a stiffness matrix, load vector, and the solution of the set of linear simultaneous equations for unknown displacements. The post-processing module then computes member end actions/forces and the support reactions.

Analysis of space frames can be divided into the following phases [Weaver,Gere].

1) Recording structural data: The user inputs information pertaining to the structure being analyzed, the data is recorded into appropriate files by the computer program. The following primary information is input by the user. The nomenclature used in the computer program is shown beside the structural parameters.
    a) Number of joints (NJ)
    b) Number of members (M)
    c) Locations of the joints (x,y and z co-ordinates)
    d) Member connectivity information.
    e) Section properties for each member
    f) The joints to be restrained (NRJ) and conditions of restraint.
2) Construction of stiffness matrix: The stiffness matrix is computed by summing contributions from individual member stiffness matrices. Table 3 shows the member stiffness matrix in member oriented axis. This step is computed by the

computer program. The program uses the data input in step 1 by the user to compute and assemble the joint stiffness matrix.

3) Assembly of load data: All loads acting on the structure must be specified. The user inputs the number of joints on which the load is applied (NLJ). The user then inputs 6 components of load, 3 forces along global x, y and z axis and 3moments about the same axis for each loaded joint. This is recorded and assembled into a global force vector by the computer program.
4) Solution phase: This phase addresses solving a set of *n* simultaneous linear algebraic equations for *n* unknowns. In this case the unknowns are the free displacements. The equations are assembled in the form of matrices and then solved for the unknown displacements by the computer program.
5) Post-processing: Using the displacements, stiffness matrix, and rotation matrices, calculate the support reactions and member end actions and the forces at various sections of the members. Stresses can be computed with calculated section forces and cross-section properties. The displacements computed in step 4 and the stresses computed in step 5 are used to evaluate different frame configurations, possible failure locations, and factor of safety for the frame. The displacement can be compared to the physical test results. A factor safety can be determined by dividing the yield strength of steel or material by maximum effective stress the frame experiences. Most design textbooks recommend a factor of safety of 2 to 2.5 for the type of structure that WMP manufactures [Juvinall,Marshek].

The data collection, or the pre-processing step, is carried out by a graphical user interface. In this module, the user inputs data such as the number of joints/nodes, the number of members, the joint or node co-ordinates, the member connectivity, the cross-sections, the loading conditions, the and fixity conditions. All of the above data are stored in different arrays which are used by the main program to compute member stiffness matrices, the joint stiffness matrix, load vectors, displacement conditions at supports, and then finally solve these system of equations to obtain the unknown displacements at all the joints of the structure. Then the post-processing module computes member actions or forces, stresses in each member, and writes this information to various text files that could be used by the end user in reports.

Description of programs

The matrix analysis of structures is written using the Microsoft VisualC++ programming language. It was more of a design decision taken during earlier part of this research work to go with Microsoft VisualC++, though several other programming languages like FORTRAN and VisualBasic could have been chosen to do the same set of tasks. The program has a main program that calls subroutines covering the following key steps. The computation of member stiffness matrix, joint stiffness matrix, rotation of axis, assembly of global force vector have been discussed in the previous sections. Figure 25 shows the overall computer program for analyzing space frames and each block of the flowchart shown in Figure 25 is described in detail in this section.[Weaver,Gere]. The flowcharts discussed in this Chapter are essentially modifications of the flowcharts discussed in the textbook “Matrix Analysis of Framed Structures” by Weaver and Gere.

1) Read and write structural data.

   a) Structural parameters

   b) Joint coordinates

   c) Member information

   d) Joint restraint conditions

2) Construction of joint stiffness matrix

   a) Compute member stiffness matrix

   b) Transfer and assemble global joint stiffness matrix

3) Read and write joint loads and construct load vector

4) Calculate and write results

   a) Solve the set of simultaneous equations

   b) Write joint displacements

   c) Compute member end actions/forces and support reactions.

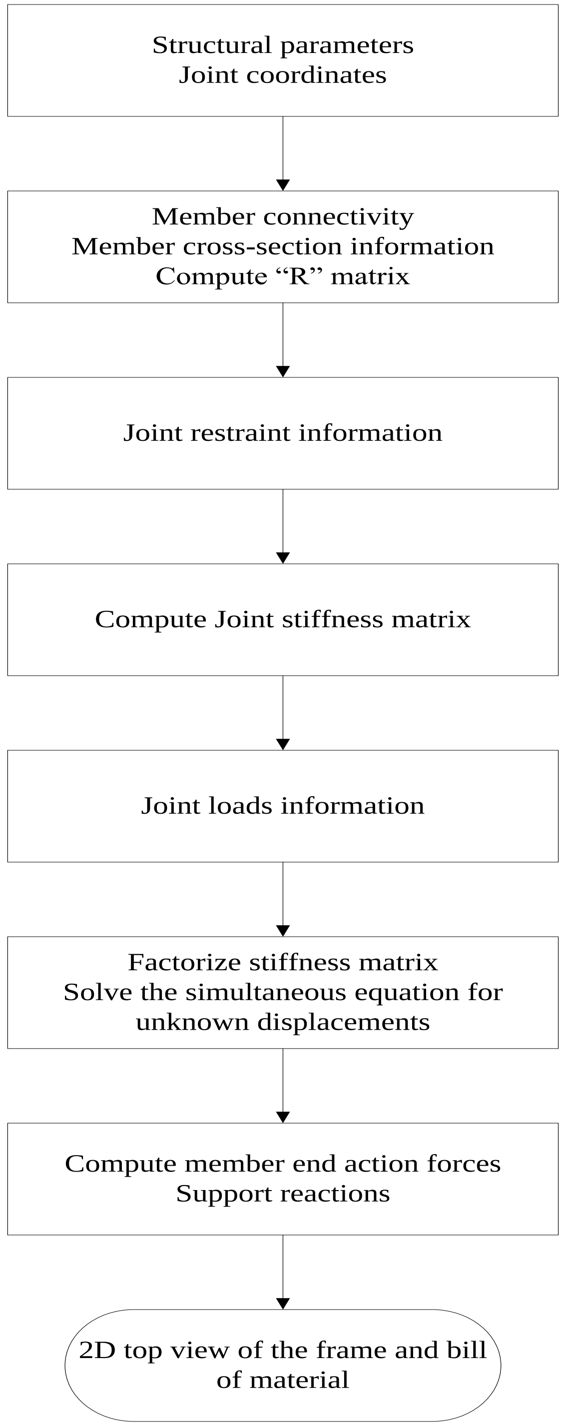


Figure 25: Flowchart of the “Design enabler tool” based on classical matrix structural analysis

The computer implementation of steps 1a and 1b is shown in Figure 26. This part of the program prompts the user to input all the structural parameters and the program loops over the total number of joints (NJ) and prompts the user to input the X, Y and Z coordinates of all the joints in the structure that is being analyzed. The structural parameters that the user needs to input are listed in the first block of the flowchart shown in Figure 26. The user inputs the following structural parameters: Number of joints "NJ", number of members "M", number of restrained joints "NRJ", Number of loaded joints "NLJ" .[Weaver,Gere]. Since WMP builds steel frames, the Young's modulus and Poisson's ratio are fixed constants in the computer program, however, the computer program can be modified to include different materials.

Figure 27 shows the implementation of step 1c. This part of the program loops over the total number of members and prompts the user to provide member information. This includes the two joint numbers "*j*" and "*k*" that connect a member "*i*" and a cross-section identification number from a pre-defined tube cross-section database that can be associated with member "*i*". The tube database contains information pertaining to the shape of the cross-section, area, and moment of inertia. The program also calculates the rotation matrices for each member and writes it to a text file. The rotation matrices are used in the joint stiffness subroutine to convert the member stiffness from member axis to structural axis system. All of the above member information is then recorded into a text file for further use.

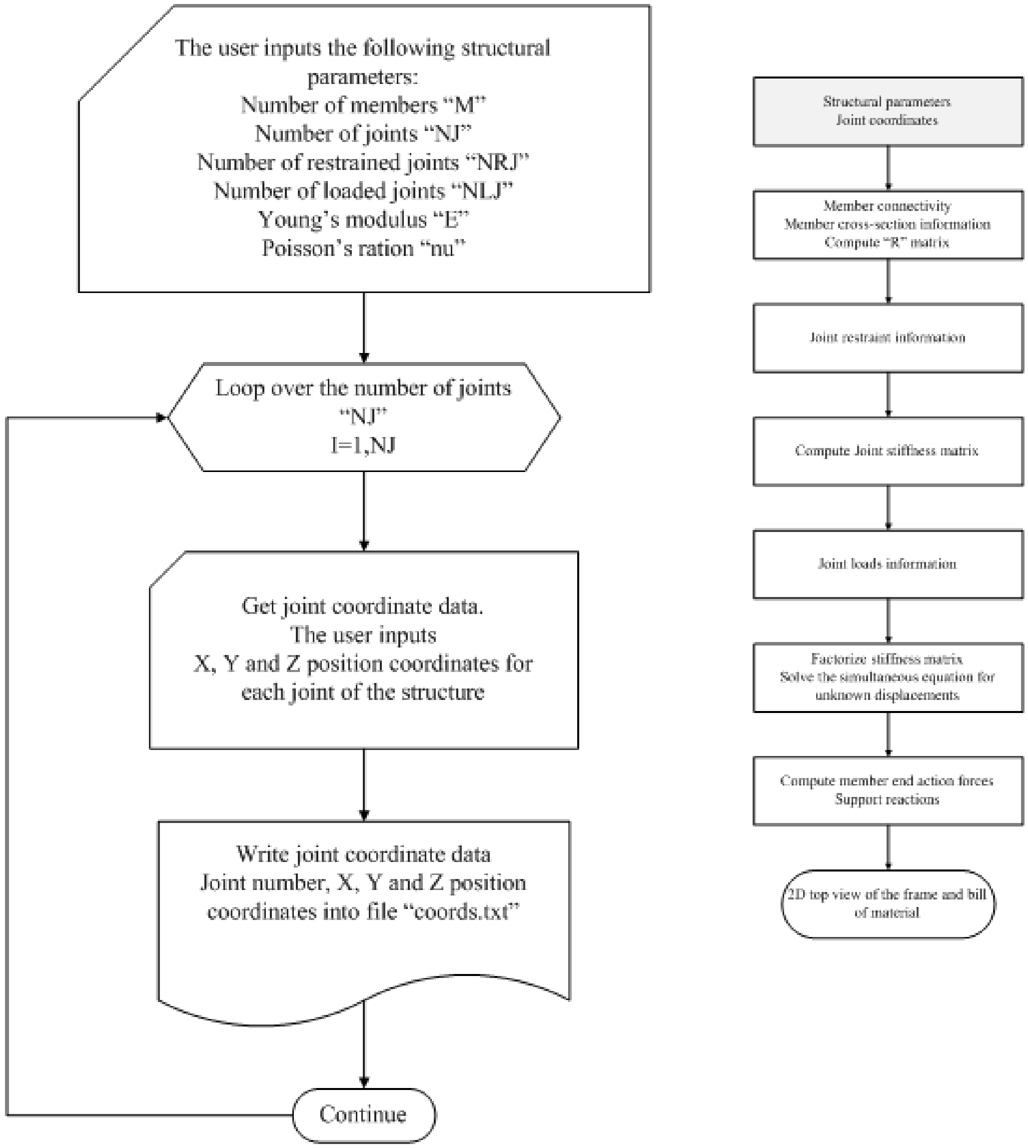


Figure 26: Read and write structural parameters and joint co-ordinates.

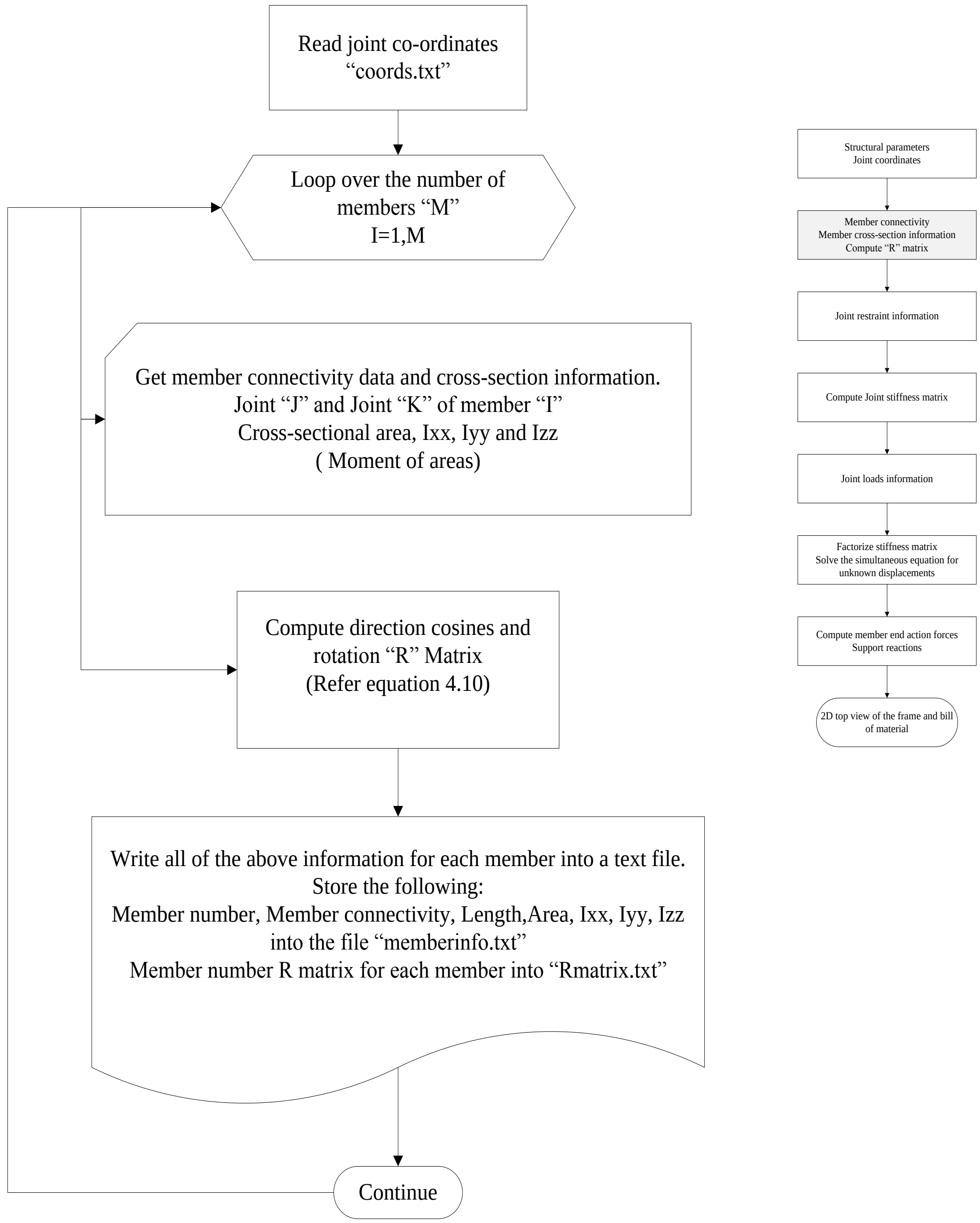


Figure 27: Read and write member information and compute rotation matrices for each member

The flowchart shown in Figure 28 addresses step 1d. The program loops over the number of restrained joints that was input in step 1a. A space frame joint has 6 degrees of freedom. The user has to provide the joint number where the structure would be restrained. To keep the program simple, it is assumed the structure is restrained in all 6 DOF at the joints specified by the user. The joint constraint vector has (6*number of joints x 1) elements. To begin with all of the elements of the joint constraint vector are "0". The program then uses node indexing to store a value "1" at appropriate locations in the joint constraints vector to account for joint restraints. This information is used during the solution stage of the main program.

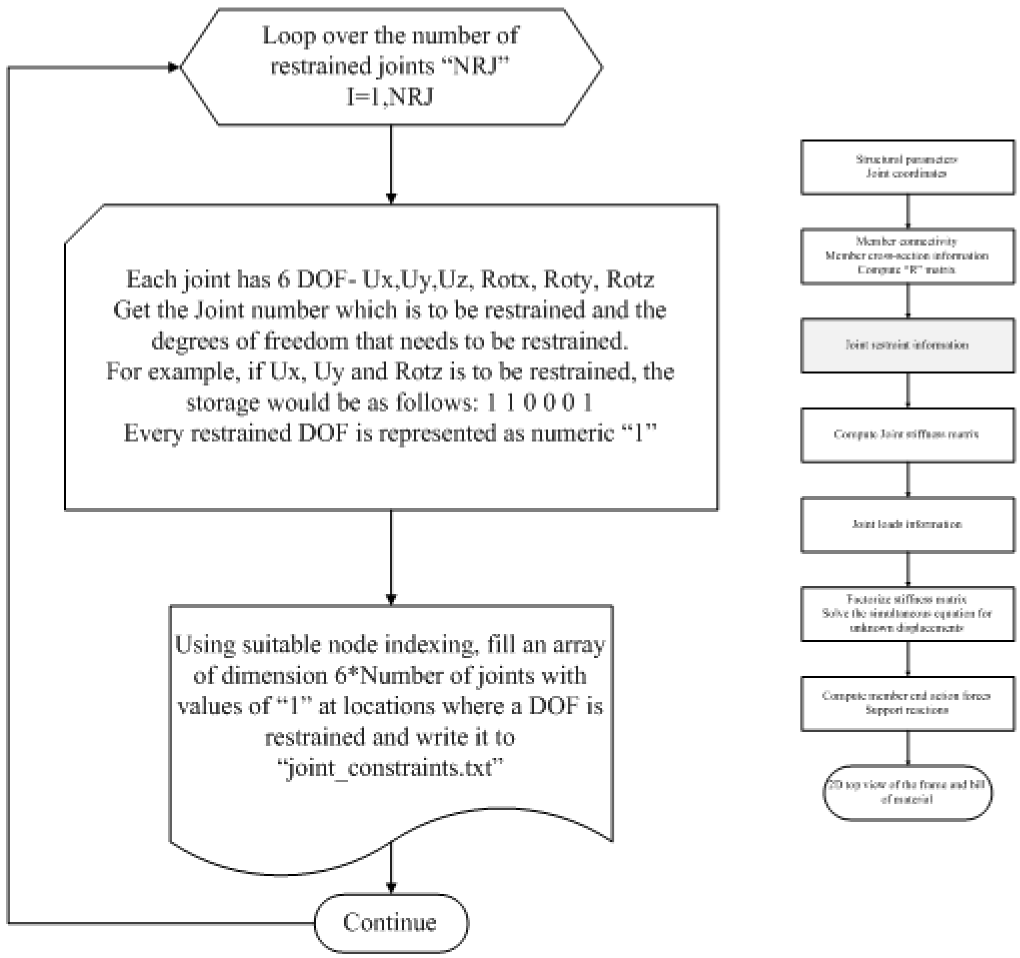


Figure 28: Read and assemble fixity conditions or restrained joints information

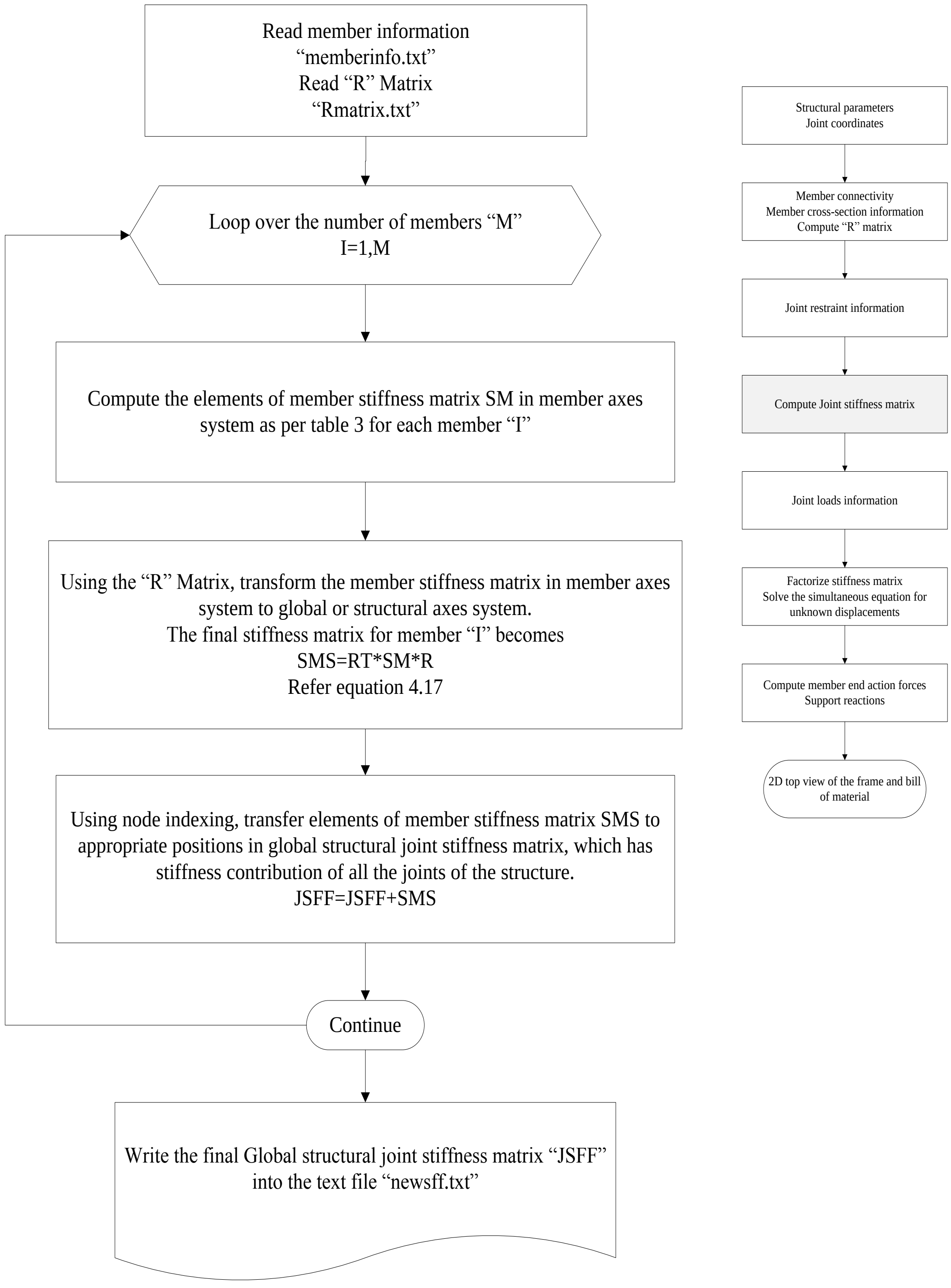


Figure 29: Computation of global joint stiffness matrix

Each member stiffness matrix in the member axis system is then converted to the structural axis system using the rotation matrix computed in step 1c and using the equation 4.17. Using node indexing, the elements of the resulting structural stiffness matrix are then transferred to appropriate locations in the global joint stiffness matrix as shown in Figure 29. At the end of the member loop, a complete global joint stiffness matrix of size (6*NJ x 6*NJ) is obtained, where NJ is the total number of joints [Weaver,Gere].

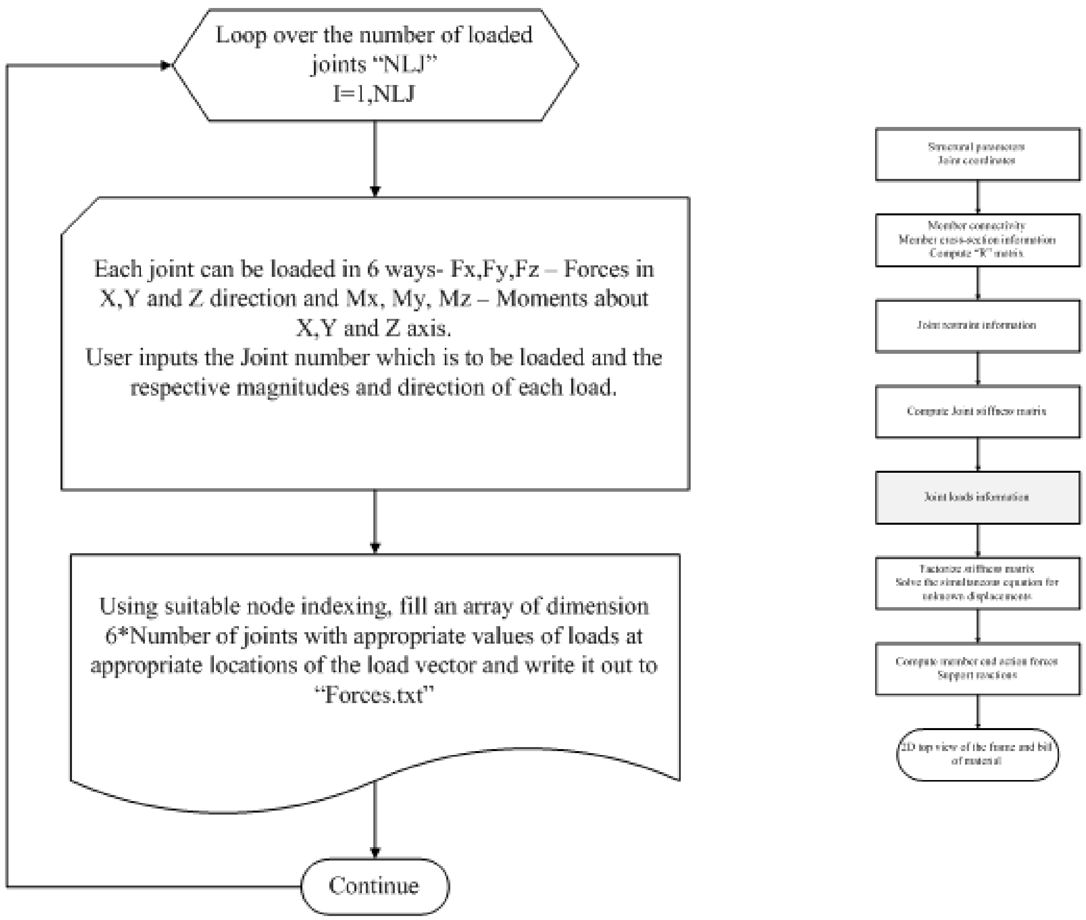


Figure 30: Read and assemble the nodal force vector for the entire structure

The flowchart in Figure 30 is the implementation of step 3. This part of the program is looped over the number of loaded joints. The program prompts the user to provide the joint number on which the load has to be applied. For the space frame member, there are 6 components of loads, three forces in three axis and three moments about the three axis. Using nodal indexing.[Weaver,Gere], the global nodal force vector is assembled. To begin with, all the elements of nodal force vector are zero and the size of the nodal force vector is (6*NJ x 1). The user specified values of forces and moments at specific joints is then placed at appropriate location using node indexing. This is the last step before solution.

At this stage of the program, assembly of global stiffness matrix and global nodal force vector has been completed. To obtain the unknown displacements, the set of simultaneous linear equations in the form $\{F\} = [K]\{\Delta\}$ has to be solved to obtain $\{\Delta\}$, the displacement vector for the entire structure. There are many methods of computing the unknowns in a set of linear simultaneous equations. This program first factorizes the symmetric stiffness matrix by a technique known as modified Cholesky method. In this method, the stiffness matrix is factored into the product of a lower triangular matrix, a diagonal matrix and upper triangular matrix.[Weaver,Gere]. Let us consider the following system of linear algebraic equations.

$[K]\{\Delta\} = \{F\}$ in which $\{\Delta\}$ is the unknown vector and $\{F\}$ is the vector whose terms are constant. The first step would be to factorize [K] matrix into $[U]^T[D][U]\{\Delta\} = \{F\}$ ………………. (4.18) [Weaver,Gere]

Where [U] is the upper triangular matrix. Due to symmetry the lower triangular matrix is the transpose of the upper triangular matrix. [D] is the diagonal matrix.

Equation 4.17 can be expressed in the following manner by introducing two new column vectors {X} and {Y}.

$[U]\{\Delta\}=\{X\}$………………. (4.19) [Weaver,Gere]

$[D]\{X\}=\{Y\}$………………. (4.20) [Weaver,Gere]

Substituting equation 4.19 in 4.20 and then into equation 4.18, we obtain

$[U]^T\ \{Y\}=\{F\}$………………. (4.21) [Weaver,Gere]

The original unknown vector $\{\Delta\}$ can be computed in three steps using the above equations. The first step is to solve for {Y} in equation 4.21. Since $[U]^T$ is lower triangular matrix, the elements of {Y} can be calculated by a series of forward substitutions[Weaver,Gere].

Second step consists of solving for vector {X} in equation 4.20. Since [D] is diagonal matrix, {X} can be found by dividing the terms of {Y} with [D] [Weaver,Gere]. Third step is solving equation 4.19 for the original unknown $\{\Delta\}$. Since [U] is upper triangular matrix, the elements of $\{\Delta\}$ are determined by backward substitution procedure [Weaver,Gere]. The above mentioned procedure was coded in VC++ to solve the equation $[K]\{\Delta\}=\{F\}$ to obtain the unknown displacements of the entire structure under the provided fixity condition and acted upon by specified joint loads.

The flowchart in Figure 31 shows the implementation of step 4c. This part of the program calculates member end actions/forces. The solution of simultaneous equations provides the values of displacements for the entire structure. The member end actions are computed in the member axis system. For a member "*i*" the force-displacement relationship is as follows.

$F_M = S_M \Delta_M = S_M R_T \Delta_S$ ………………. (4.22) [Weaver,Gere]

Where, Δ_M is the set of joint displacements in member axis system and Δ_S is the set of joint displacements in structural axis system. The support reactions are then computed using the results from member end action as follows.

$RF = R_T^T S_M R_T \Delta_S$ ………………. (4.23) [Weaver,Gere]

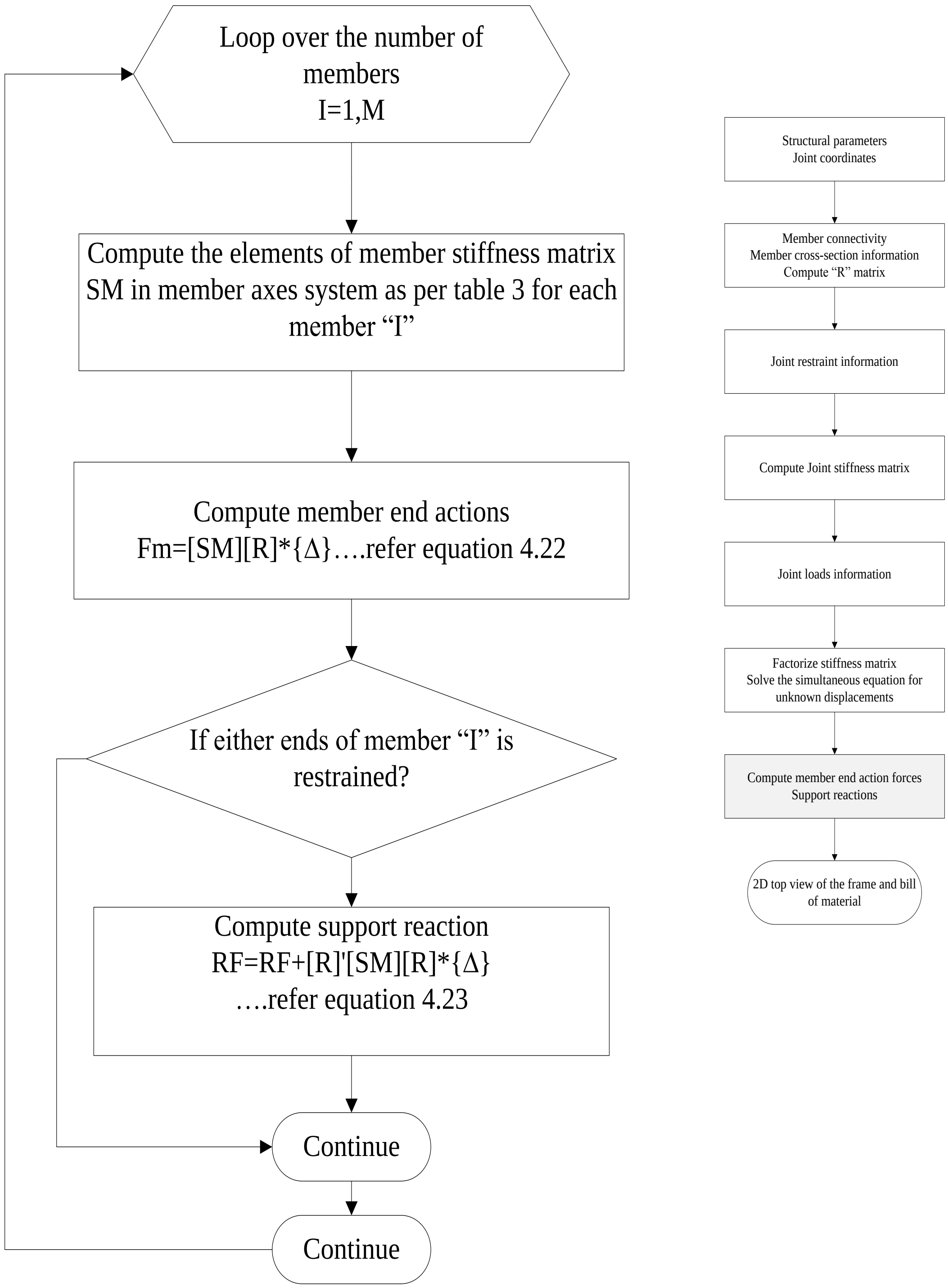


Figure 31: Compute member end actions and support reactions

RF is the reaction force. Contributions to RF will be from those members that frame into the supports. The support reactions are computed in the global axis system [Weaver,Gere].

After computing member end actions and support reactions the Tool then plots a 2D top view of the frame showing the widths of the tubing and listing a bill of materials used in the frame. This figure is stored in the form of a jpg file.

Tool demonstration

The frame designer needs to sketch the frame that needs to be analyzed on paper and include details like dimensions, node/joint numbers and member numbers. There is no particular technique for numbering the joints and members of a frame.

To start the tool, click on the icon "WMP-frame analysis"

This is the first screen that appears is shown in Figure 32.

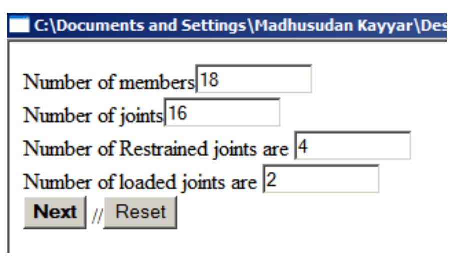


Figure 32: First screen of the design enabler tool

The user needs to input the number of members, joints, number of restrained joints and the number of loaded joints. Then "click" on the next button.

The next screen to appear will be as shown in Figure 33

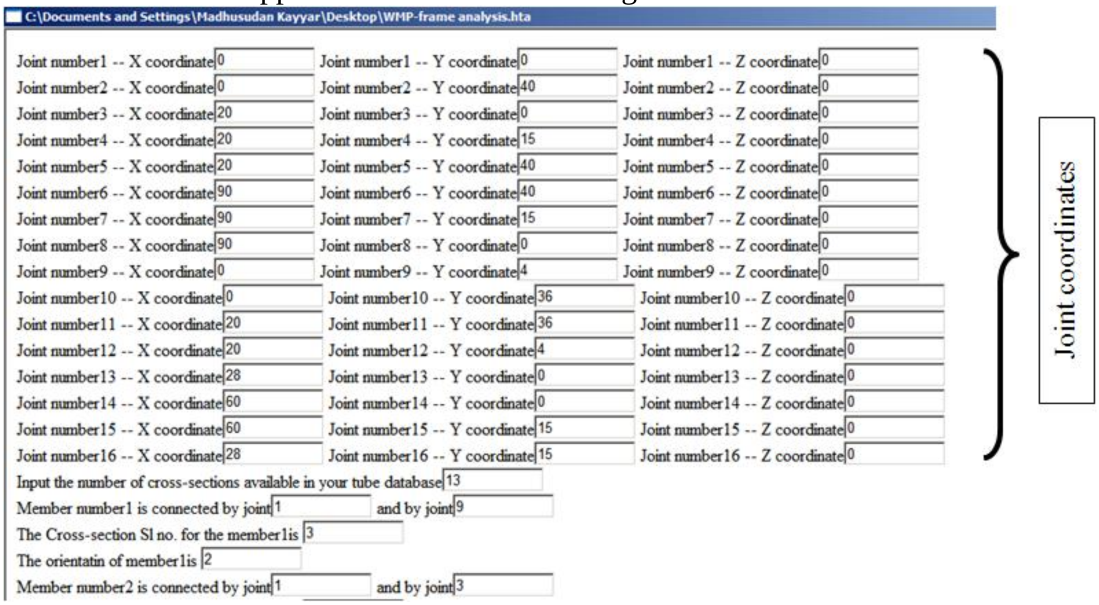


Figure 33: Second screen of the design enabler tool.

The user must input the X ,Y and Z coordinates for each joint of the frame. In most cases "Z coordinate" is 0. This is because most frames that are analyzed can be approximated as planar frames having X and Y coordinates only.

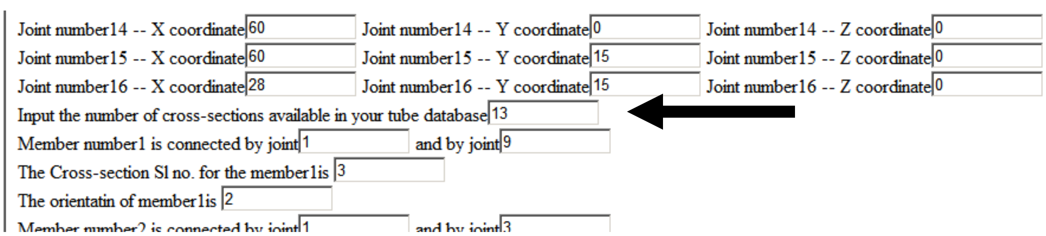


Figure 34: The number of cross-sections available in WMP tube database

The user then inputs the number of cross-sections available in WMP tube database. A Microsoft Excel based tool was developed to compute the tube cross-section properties so that the user only needs to input the tube serial number for a specific member of the frame. The program automatically computes all the tube cross-section information needed for computation of the stiffness matrix.

The next step is to input “Member connectivity”

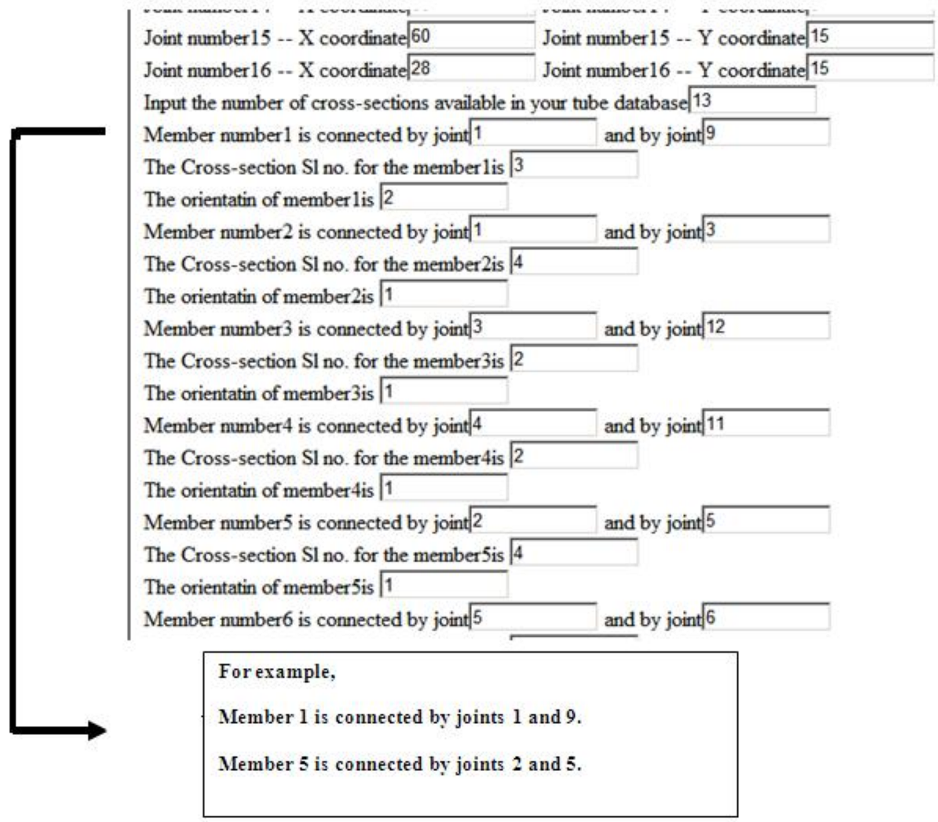


Figure 35: Defining member connectivity

The user inputs member connectivity for all the members of the frame as shown in Figure 35. Figure 36 shows the possible tube orientations and can have two values, 1 or 2. Consider a tube from the tube database with width being 1" and height being 3". The following are two possible orientations.

Figure 36: Possible tube orientations of a rectangular cross-section

The user can choose a tube and decide its orientation by specifying 1 or 2 in the orientation row of the input window.

The end of the input window is as follows.

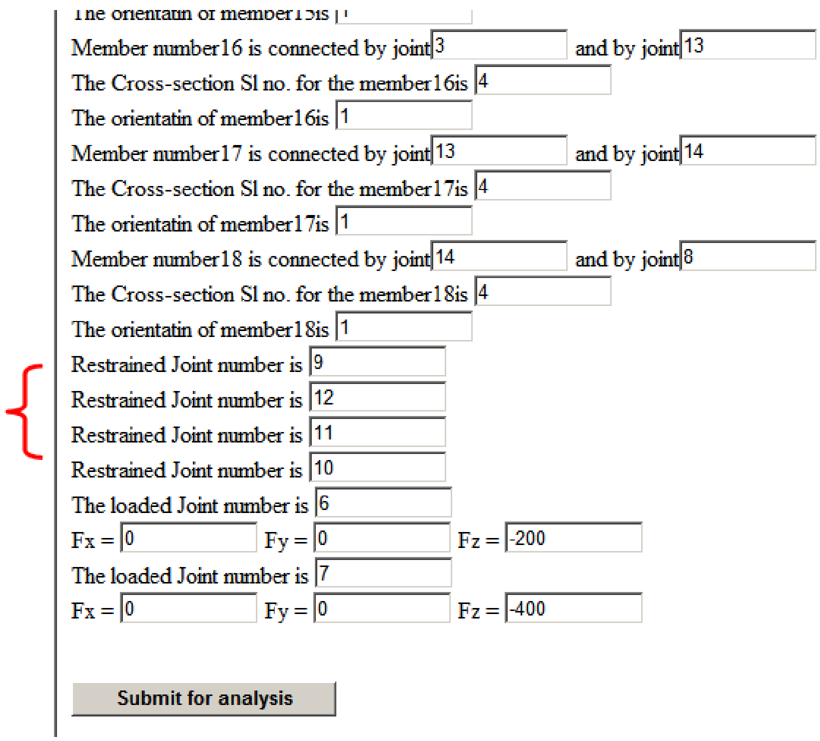


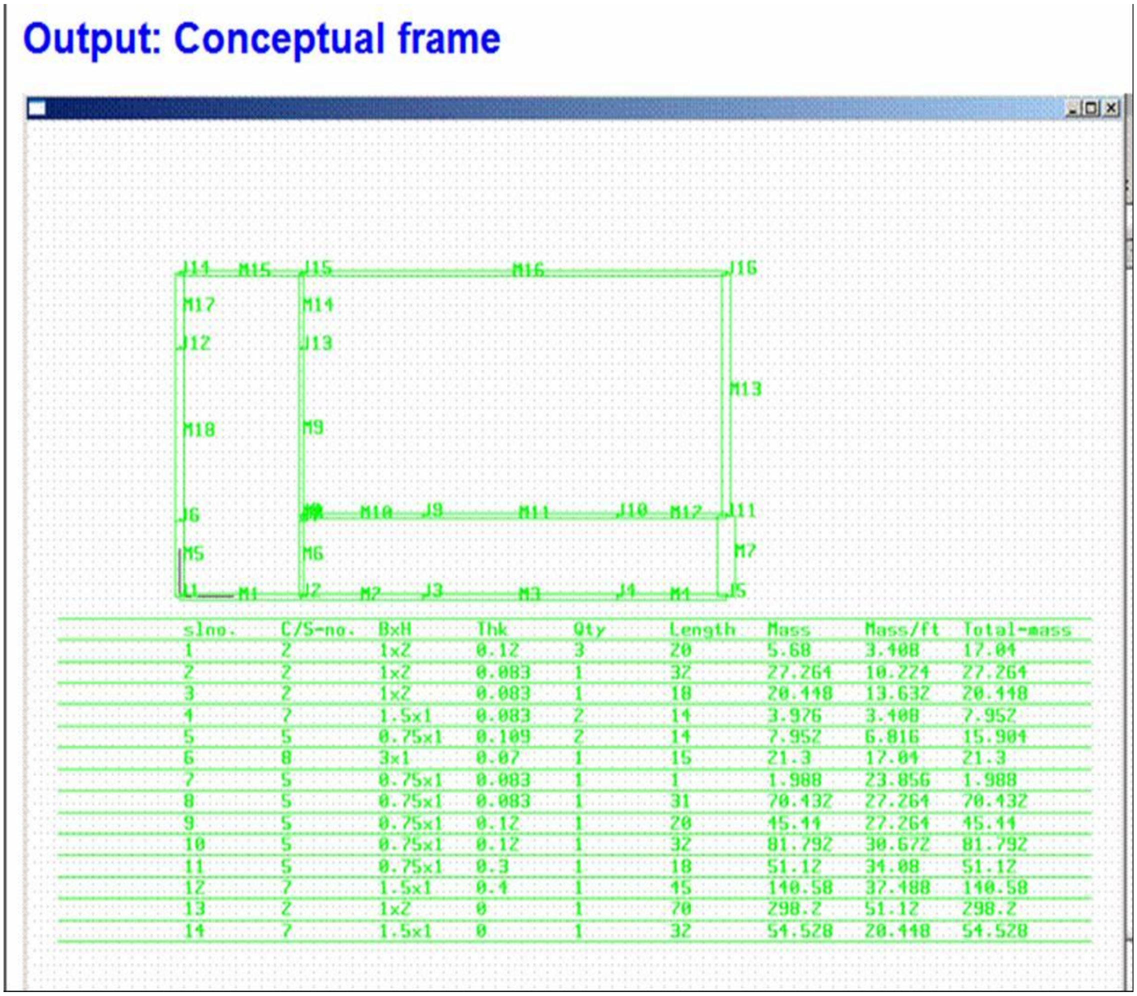
Figure 37: Input restrained joint/node numbers and joint loads

The user inputs the restrained joint numbers as shown in Figure 37. It is assumed that the user wishes to restrain all degrees of freedom for a specific joint. The program can also handle restraining selective degrees of freedom for a joint. The modification in the input dialogue box is done for simplicity.

The user then inputs the loaded joint number and the loads in X, Y and Z direction as shown in Figure 37. Here too, the program can handle moments about X, Y and Z axis but moment loads are rare on the frames that WMP designs. Furthermore these moments could be represented in terms of forces and therefore the modifications in the input dialogue box are for simplicity.

The final step is to click on the "Submit for analysis" button.

Once the structure is submitted for analysis, the computer program does all the engineering calculations and writes the deflection, member end actions and support reactions into text files. Then the graphics module plots a 2D drawing of the frame with bill of material as shown in Figure 38.



slno.	C/S-no.	BxH	Thk	Qty	Length	Mass	Mass/ft	Total-mass
1	2	1x2	0.12	3	20	5.68	3.408	17.04
2	2	1x2	0.083	1	32	27.264	10.224	27.264
3	2	1x2	0.083	1	18	20.448	13.632	20.448
4	7	1.5x1	0.083	2	14	3.976	3.408	7.952
5	5	0.75x1	0.109	2	14	7.952	6.816	15.904
6	8	3x1	0.07	1	15	21.3	17.04	21.3
7	5	0.75x1	0.083	1	1	1.988	23.856	1.988
8	5	0.75x1	0.083	1	31	70.432	27.264	70.432
9	5	0.75x1	0.12	1	20	45.44	27.264	45.44
10	5	0.75x1	0.12	1	32	81.792	30.672	81.792
11	5	0.75x1	0.3	1	18	51.12	34.08	51.12
12	7	1.5x1	0.4	1	15	140.58	37.488	140.58
13	2	1x2	0	1	70	298.2	51.12	298.2
14	7	1.5x1	0	1	32	54.528	20.448	54.528

Figure 38: 2D drawing of the frame with bill of materials

However, interpreting the results from the Tool becomes complex for a non engineer. Therefore, to start with, the designer could arrive at an overall deflection value for the frames that are currently in service and are operating satisfactorily. The baseline deflection could be determined from tests and this deflection can become a goodness measure for future designs. While designing a frame using the Tool, if the designer comes across a deflection higher than the prescribed value, steps can be taken to redesign the frame and re-analyze to ensure that the deflection are within safe limits or baseline deflection. The Tool is suitable for determining global deflection and stiffness but will not aid the designer in modeling stiffness/deflection of local connections, and other detailed features. Stress results are also global in nature and may have limited use in modeling specific features like the female cup and male boss shown in Figure 11. Hence the Tool should be used at the conceptual stage of the frame design in arriving at a preliminary frame configuration and determining the cross-sections of individual frame members. It should also be noted that the tool does not account for stability/buckling of long frame members in compression, or local buckling/warping of cross-sections. To account for all of the above factors, a more sophisticated tool and more importantly an engineer would be required to analyze and interpret the results.

Tool testing

The frame shown in Figure 39 is analyzed using the design enabler tool and ANSYS. Joints 1 and 2 are fixed in all degrees of freedom. Loads are prescribed on joints 6, 7 and 8. The values of load, the joint number, member number and cross-section numbers are shown in Figure 39.

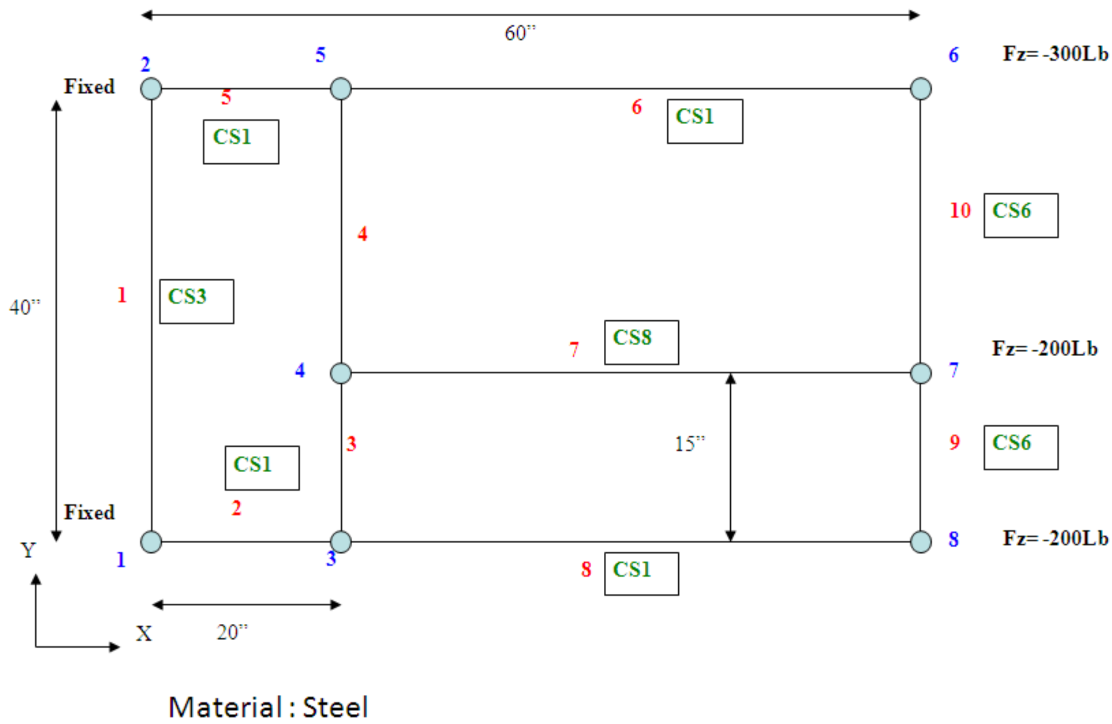


Figure 39: Frame configuration used to test the tool

The results are shown in

Table 6.

Table 6 Comparison of displacements calculated from the Design enabler and ANSYS

Joint no.	Displacement	Design enabler tool	ANSYS
3	Ux	0	0
	Uy	0	0
	Uz	-0.38075	-0.38075
4	Ux	0	0
	Uy	0	0
	Uz	-0.3993	-0.39929
5	Ux	0	0
	Uy	0	0
	Uz	-0.39368	-0.39367
6	Ux	0	0
	Uy	0	0
	Uz	-2.59562	-2.5956
7	Ux	0	0
	Uy	0	0
	Uz	-2.56683	-2.5668
8	Ux	0	0
	Uy	0	0
	Uz	-2.51834	-2.5183

Ux, Uy and Uz are the displacements in X,Y and Z direction. The displacements computed using the Tool and ANSYS are the same to 4 significant figures.

Tool validation

A help file was created to assist the user while using the tool. The help file was also used in training the users in operating the tool. A 4-hour training session was conducted to demonstrate the tool at WMP. The training was conducted using an actual example of a frame that is being manufactured at WMP. The user was taken through the step-by-step procedure of analyzing the frame. At the end of the training session, the user provided valuable suggestions on the tool and possible improvements that would make the tool more user friendly. The step most prone to error in using the tool is keying in the numerical data such as, the joint coordinates and the member connectivity. To avoid errors due to keying in information, the user suggested the use of the Soildworks package to generate a 2D drawings of the initial frame configuration and then importing it to the design enabler tool. The other suggestion was to visually represent the results obtained. Both of these suggestions are valid and could be implemented in the future versions of the tool. These suggestions are further discussed in Chapter 5. The current Tool forms the foundation for development of enhanced versions of the same, that includes rule-based systems, optimization, and case-based reasoning that would assist designers in efficient product development.

CHAPTER 5

FUTURE SCOPE AND CONCLUSIONS

Conclusion

From this study, it is observed that WMP's current product design process relies heavily on past experience of select employees within WMP. Improving the design process requires the integration of systematic design procedures and the creation of an interface in the form of "Design Enablers" to incorporate engineering knowledge as driving factors in crate design. The role of the "Design Enablers" is to assist the designer at various stages of the design cycle and not to eliminate or completely automate the design process. Furthermore, the "Design Enabler flow-networks" could be generalized and used in other industries that currently depend on a few key experienced individuals designing products based only on experience without using any sort of engineering tools in the design process. However, before developing new tools illustrated in Figure 42 and Figure 43 or making any improvement on the existing design enabler tool, it is important to evaluate the usefulness of the current Tool in the actual work environment. The future study should try and measure the improvement of designs, enhanced creativity and design efficiency of the designers at WMP with and without the use of the Tool.

WMP needs to incorporate simple yet effective design tools like requirements checklist, and a customer specification sheet into their current design process. The tools are available in most design text books listed in the references and need to be tailored to make them more specific to the product that WMP designs. Incorporating such design tools would initiate a culture of data collection and create a design database that is product and process specific. This would also give a chance to the design team to periodically review the data collected and make further improvements in the design process. Such a systematic approach to not only document the design but also the process of arriving at a specific design would ensure the activity of designing to be process dependent. It would give an opportunity for the management and the designer to pinpoint the areas for improvement, identify design challenges encountered in the past designs, and promote out of the box thinking for new designs.

Documenting the final design is an important step WMP follows currently, however lessons learned during the design cycle need to be documented for future reference. A repository of failures and successes would ensure better designs at the conceptual stage. A database of the "Rules of thumb" used extensively by current frame designers would help a new frame designer immensely in learning the finer nuances of frame designing. These rules of thumb are currently used throughout the design cycle: from the conceptual stage to the mass production of the designed product. Building a design database comprising "rules of thumb", past success and failures, manufacturing rules, repository of designs, prototype testing and results, repository of various concepts of frame configuration, and augmented with design tools in the form of various checklists could be envisioned as the foundation for future frame designs.

The result of the case study illustrated in Chapter 2 is the development of a "Design Enabler tool" that can be used to analyze different frame configurations at the conceptual design stage. Analysis of frames is the key missing aspect in the current design process of designing frames. Without analysis, the designer is unable to answer the question "How good is my design" at the conceptual stage without having to build and test a frame design. The Tool assists the designer in modeling and analyzing a frame configuration without having to physically building one. The tool outputs the deflection at each joint of the frame which is key parameters while comparing different frame configurations and comparing to a deflection limit derived from past successful designs. The tool would empower the frame designer to analyze different frame configurations under various simulated operating conditions. The designer is then able to rank different designs based on deflection. This tool can be termed as a virtual prototyping tool. The designer is then able to determine the merits and demerits of a frame design. The time required to model and analyze a frame configuration is few hours as compared to 1 week to physically prototype a frame. Furthermore, for a specific frame configuration, the frame designer is able study the response of the frame in terms of stress and deflection for different tube dimensions and gauges. This would empower the designer to think out of the box and explore the available design space in a time efficient manner.

Currently, the frame designer chooses the tube dimensions and builds a frame configuration purely based on his experience and does not have any information on the deflection until physical tests are conducted on the frame using the actual vehicle. The designer is constrained by time and money and is able to run limited number of tests on the designed frames. However, the design enabler should not be considered as a tool to replace prototyping and testing of a finished product. WMP still needs to build and test the final design to meet customer specifications. The frame designers that WMP currently employs are not engineers and this is an important factor that was considered while building the Tool. The underlying physics and computer implementation of the Tool is illustrated in Chapter 4. A graphical user interface, which is a part of the Tool, allows the user to input the necessary data to build and analyze a frame design. A few engineering details like materials, certain loads and boundary conditions are assumed based on the products WMP designs.

The extensive use of the Tool would result in the management making an informed decision on costing, finalizing the frame design and WMP would have greater confidence while testing and designing the frames with the aid of data generated by the enabler. Eliminating the trial and error method of designing products would reduce prototyping costs and design cycle time required for designing frames. However, without a post implementation study of the design enabler tool, we cannot conclude and completely answer the research question stated in the introduction-"Can a computer aided design enabler tool be developed for a Company that heavily relies on a few key individuals with no formal design or engineering background". At this point, we can conclude that a design enabler tool has been developed which from an engineer's perspective can have an impact on the way frame design is carried out at WMP and a post implementation study is needed to determine as to whether the design enabler tool has made an impact on the way a frame is designed by a designer with limited formal engineering expertise.

Future scope of the design enabler tool

The current Tool which has an engineering analysis module and a display module is the foundation for extending the scope to include optimization, rule-based systems and case-based reasoning. Figure 40 shows the enhancements that need to be carried out on the existing Tool. These enhancements could be implemented before moving to a knowledge based system shown in Figure 42 and Figure 43. Rearranging the graphics module such that the frame configuration is displayed before entering the solution module would be beneficial for the user. An addition of a decision subprogram after displaying the frame configuration could help the user to choose to go ahead with the solution or to go back and correct a mistake, then proceed for solution. The current program does not have the decision subprogram. Hence if the user makes a mistake in keying in the values, the user is forced to repeat the whole process.

In the current tool, the results are stored in the form of text files. A graphical representation of displacements and stresses across each member would be an effective way to display the results.

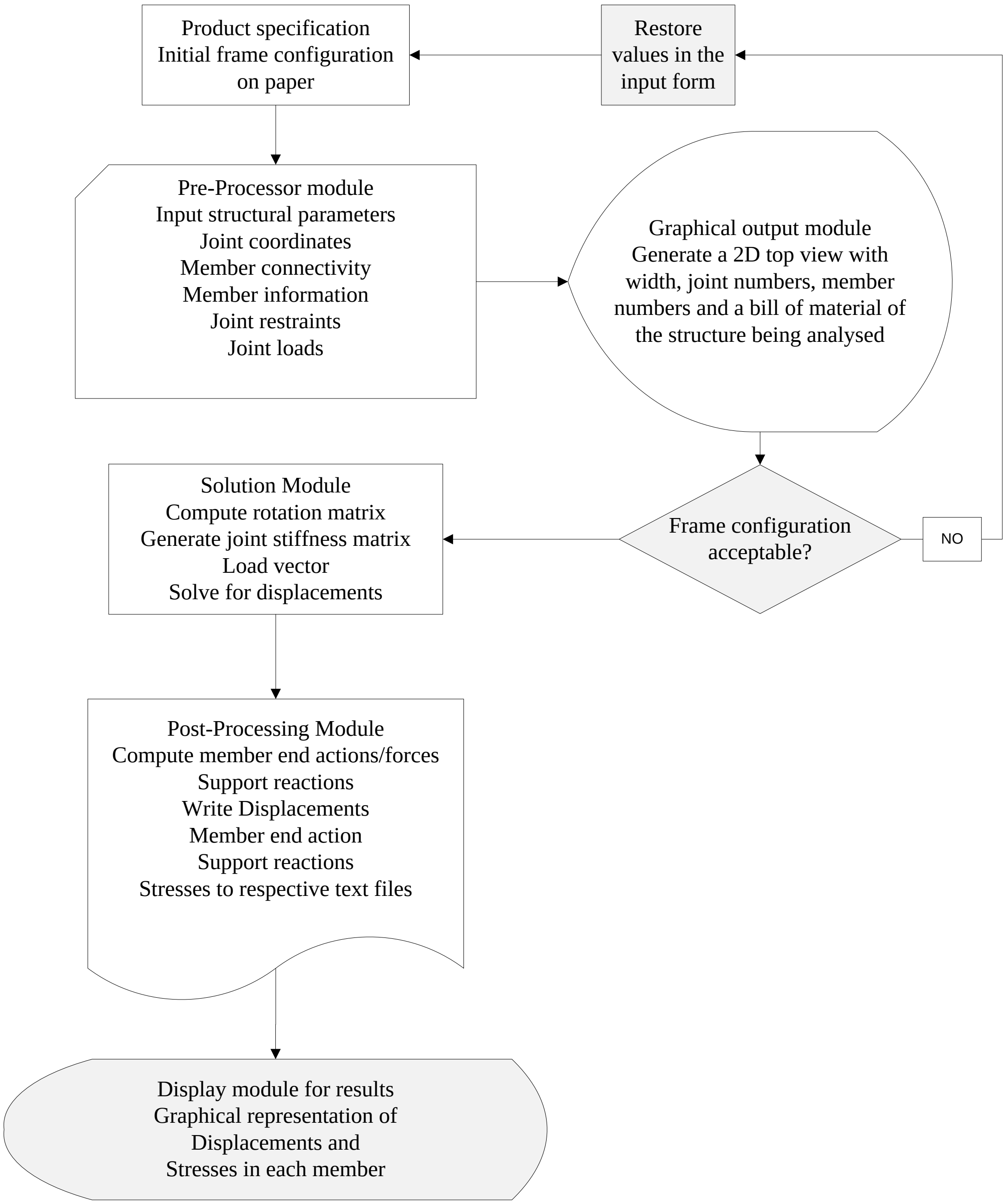


Figure 40: First phase of enhancement for the design enabler tool.

The suggestions obtained from the training session provide by the users can be implemented in the first phase. The concern was the error in keying vast amounts of information, primarily the joint coordinates and member connectivity. Solidworks drafting or parametric sketching can be used as a work around. Only a line sketch is required to represent a frame configuration. This sketch can be exported in "dxf" format which is essentially a text file. A program can be written to segregate line information, i.e., the x, y, z coordinates of two points defining the line. All information regarding joint coordinates and member connectivity can be processed using the dxf file. This would reduce incorrect input from the users end. The rest of the design enabler tool would remain the same.

Rules-based and product-family-based design enabler tool

This design enabler is based on vast knowledge base. This knowledge base comprises of design rules, product families, material database and operating conditions. Design rules could comprise of DFM rules, similarity rules, packaging rules, transportation rules, loading and unloading rules, error proofing rules and stacking rules. These rules are currently being followed subconsciously by the frame designer. The frame designer needs to document the rules that are currently being followed. Product families comprise past successful designs, design databases and CAD models. Operating conditions are essentially comprised of loading scenarios and testing scenarios. The loading scenarios are the forklift conditions and stacking conditions and testing scenarios are the formal tests of different customers. Figure 42 shows the rule-based and product-family-based design enabler tool.

With an extensive knowledge base and efficient search algorithms it is possible to write programs that would output a set of frame configurations based on the inputs provided. Once a concept frame configuration is ready, an initial guess of tube sizes can be used to solve the frame configuration for different load scenarios. The optimization module outputs the top 5 feasible solutions along with the possible tube cross-sections for each member. Then the management can take a decision on the final frame design. A preliminary optimization study was conducted on one specific frame configuration that WMP manufactures using the commercial FEA code ANSYS. The frame configuration is optimized to obtain optimum values of tube cross-section dimensions. Figure 41 shows the initial and final frame configuration. The Table 7 shows the optimized values of tube dimensions for each frame member.

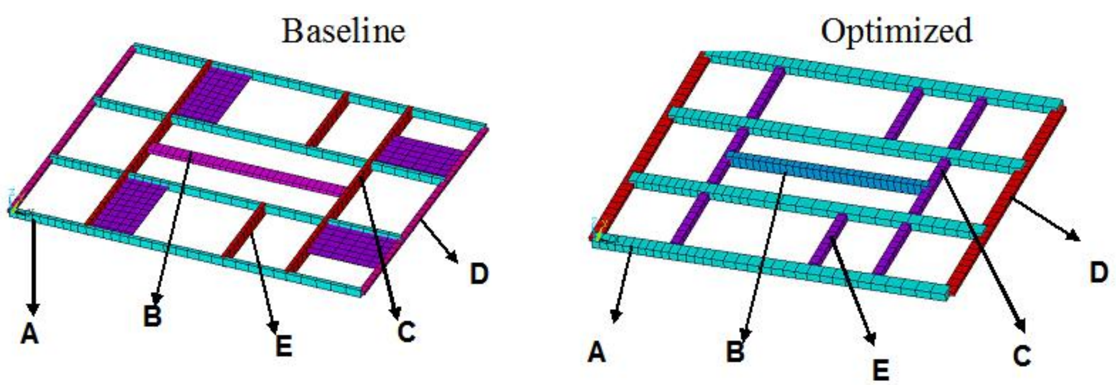


Figure 41: Baseline and optimized frame design

Since we know that the current frame design works fine during actual operation, the stress levels in the current baseline are used as a constraint during optimization. This means the factor of safety is the same for the baseline and optimized frames. The results shown in Table 7 are based on 2 stack high loading and fork-lifted from the rear end of the frame. The base frame weighs 122 Lbs (excluding the sheet metal and small components) and the optimized frame weighs 80 Lbs.

Table 7: Optimization results and weight savings

2-Stack High

Baseline

ID	Number of members	width	height	Thickness	area	length	volume	**Weight**	weight/ft
A	4	1	2	0.12	0.6624	87	230.5152	**65.46632**	2.257459
B	1	1	3	0.083	0.636444	52	33.09509	**9.399005**	2.169001
C	2	1	3	0.083	0.636444	70	89.10216	**25.30501**	2.169001
D	2	0.75	1.5	0.083	0.345944	66	45.66461	**12.96875**	1.178977
E	2	1	3	0.083	0.636444	23	29.27642	**8.314504**	2.169001
							427.6535	121.4536	

Optimized

ID	Number of members	width	height	Thickness	area	length	volume	**Weight**	weight/ft
A	4	3.25	2.25	0.04	0.4336	87	150.8928	**42.85356**	1.477709
B	1	2	3.25	0.01	0.1046	52	5.4392	**1.544733**	0.356477
C	2	2.25	1.75	0.05	0.39	70	54.6	**15.5064**	1.32912
D	2	3	1	0.05	0.39	66	51.48	**14.62032**	1.32912
E	2	2.25	1.75	0.05	0.39	23	17.94	**5.09496**	1.32912
							280.352	79.61997	

The total weight savings is 42 lbs. However, the weight savings need not necessarily translate to lower cost. If the frame designer is able to perform the optimization during the conceptual stage, it would be helpful in arriving at a cost effective frame design.

The other alternative is to develop a case-based system as shown in Figure 43. This system of design emphasizes storing design information such as product specifications, details of earlier successful frames, standard inputs to a design, test data, etc. Using this vast information resource, it is possible to develop a design enabler that would aid in developing a unique solution for the new scenario [J.Kolodner].

Both the design enablers shown in Figure 42 and Figure 43 require an extensive knowledge database. These databases cannot be generated in a short period of time and require huge investments on the part of management. These models of design enablers are more suitable for a large scale industry with high product turnover. Such companies can afford to invest in such a system and specialized manpower to operate and maintain such a system.

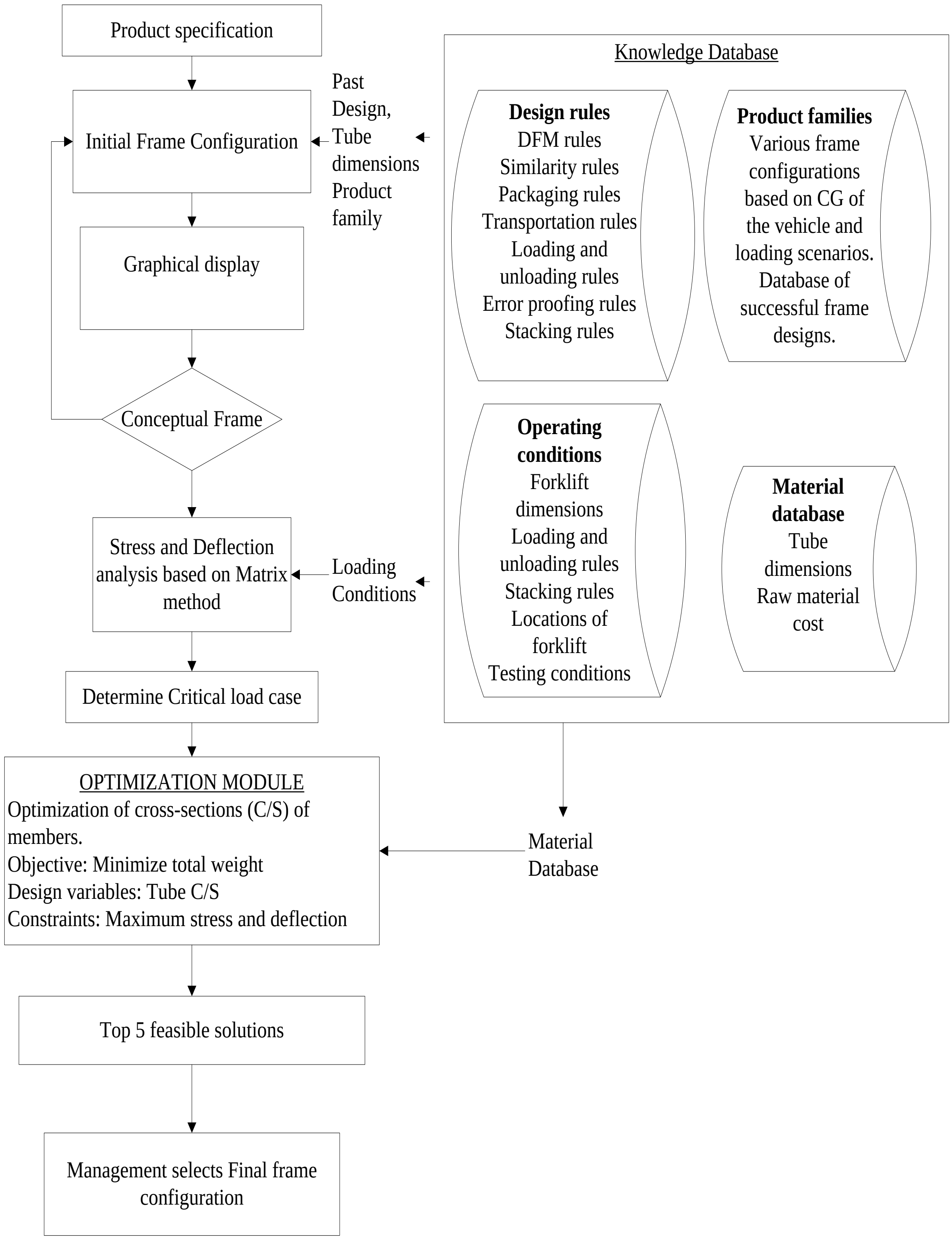


Figure 42: Rules-based and product-family-based Design Enabler Tool

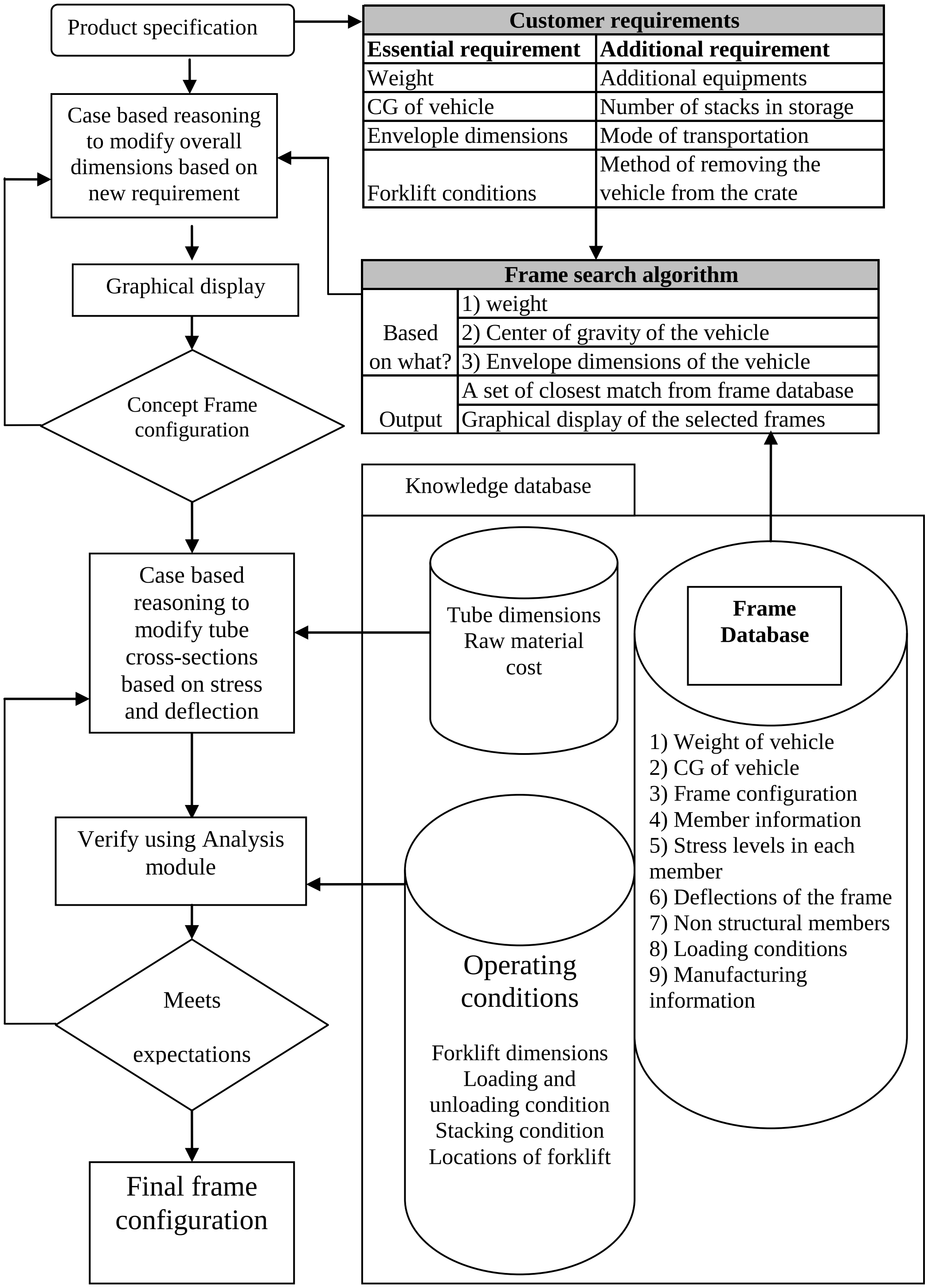


Figure 43: Case-based reasoning Design Enabler tool

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